Domestic Air Conditioning in Malaysia: Night T
Thermal Comfort and Occupants Adaptive Beha

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Declaration

I, Mohamad Fakri Zaky bin Ja'afar, confirm that the work presented in this thesis is to the best of my knowledge and belief, original and my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Mohamad Fakri Zaky bin Ja'afar

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Abstract

This is the first study of night time thermal comfort in Malaysia as well as the first study of sleeping comfort level. The focus of the investigation, the use of air-conditioners in homes clearly indicates a problem. Evidences of overcooling (76% of the cases) and sleep interruptions (45% of cases) to adjust control are found. In around 38% of the cases, the internal thermal profiles never reached a stable condition; instead they keep cooling throughout the night until the units are turned off in the morning. The act of putting on a thicker, comforter type blanket, more of a psychological choice than a physiological need, during air-conditioned occupancy, results in people operating their air-conditioners at lower than the optimum temperature level. A thermal comfort field survey was conducted by monitoring 29 air-conditioned bedrooms, investigating the environmental conditions, the corresponding comfort perceptions and occupants' adaptive behaviour. Thermal neutralities and thermal acceptability for night-time occupancy in air-conditioned homes are established. Statistically significant difference is found between the neutral air temperature of normal blanket users (27.5°C) and that of comforter users (25.2°C). Thermal acceptability and comfort range for each group have also been established. A simulation study was conducted and it shows that the choice of using a comforter as opposed to a normal blanket results in an increase of up to 52% in the cooling load of a bedroom. This finding suggests that adaptive behaviour does not always result in less energy being used for comfort provision when active cooling is employed.

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List of abbreviations

AC	*Air Conditioner, Air conditioning*
ASHRAE	*American Society of Heating and Refrigerating Engineers*
ASHVE	*American Society of Heating and ventilation Engineers*
Clo	*Clothing insulation value*
COP	*Coefficient of Performance*
EER	*Energy Efficiency Rating*
ET	*Effective Temperature*
FCU	*Fan Coil Unit*
GBP	*British Pound Sterling*
Met	*Metabolic rate*
MYR	*Malaysian Ringgit*
OCU	*Outdoor Condensing Unit*
PMV	*Predicted Mean Vote*
PPD	*Percentage People Dissatisfied*

PART I: LITERATURE REVIEW

1 Introduction

In tandem with the country's consistent economic growth, as with many other consumer goods, the use of air-conditioners in Malaysian homes is growing steadily. Accounting for as much as 20% of energy consumption in households, air-conditioners could soon be the single largest energy consuming device in the domestic sector. The use of air-conditioners in Malaysia has been rising for the last 15 years. In 1991, 7.1% of households had at least one air-conditioning unit installed [1]. By the year 2012, the percentage is predicted to be 16%, consuming as much as 15-20% of all energy use in homes [2]. However, the prediction model did not include the impact of global warming. Rising ambient temperature may further increase the rate of growth of air-conditioners in Malaysian homes, therefore, the prediction may underestimate the actual number of households using air-conditioners in the coming years. With the number of households installing air conditioners continues to increase; it is clear that achieving energy efficiency in this sector is a priority. As such, there is a need to evaluate the energy use by this appliance, as well as predicting the energy demand arising from the growth of its use.

In order to establish a clearer picture of energy requirements in this sector, there are two other related areas of investigation which need to be addressed beforehand. First, the thermal comfort requirements in residential settings need to be identified. Secondly, users' behaviour in the use of air-conditioners has to be understood, both in operating the air-conditioners, and in adaptive actions taken in achieving comfort. The investigation into these two areas of air-conditioning use in Malaysian homes is the main focus of the current study.

The need to establish the comfort conditions necessary for the occupants then becomes the first line of inquiry of the current study. Thermal comfort studies have been conducted by many researchers all over the world to cover a wide range of situations and needs. In Malaysia, thermal comfort studies have been conducted to cover office buildings, factories and schools. However, no study of thermal comfort in homes has been conducted. The current study thus has the importance of being the first to look into the residential setting.

1.0 Background of study

The use of air-conditioners in Malaysia is not new. Air-conditioners were first introduced in Malaysia back in the 1970s. Investigation into available literature on air-conditioning use in the domestic sector in Malaysia reveals little more than the annual number of households with air-conditioners. In order to draw a clearer picture of the energy scenario, more information is needed. The two important aspects which have been discussed above, i.e. the thermal performance and the use pattern of air-conditioners were unavailable at the time of the study.

In assessing the thermal performance of air-conditioners, it is necessary to understand the required comfort level of occupants as well as the prevailing environmental conditions. Assessment can then be carried out to evaluate how well the provided thermal conditions match this requirement. Investigation into these aspects can be approached through a thermal comfort study. This research is a well structured discipline which is the main mode of investigation adopted for the current study.

Many researchers have conducted studies of thermal comfort in Malaysia. At present, thermal comfort studies conducted in Malaysia have covered office situations [3], schools [4, 5] and factories [6, 7]. A climate chamber study has also been conducted, but with subjects limited to a specific group of a student population [8].

Several studies on the environmental performance of residential buildings in Malaysia can be found in the literature [9-12]. However these studies do not provide enough information to establish an adequate thermal comfort assessment for the domestic sector. It is the intention of this study to fill this gap, providing information of thermal comfort in dwellings employing the use of air conditioning units.

1.1 Motivation for study

The study stemmed from the author's curiosity regarding problems in the use of air-conditioners in Malaysian homes. From the author's personal experience, two important observations were the impetus for the current study. First, there is a need to interrupt sleep in order to adjust the operation of the units in the early mornings, because it often gets too cold by then. This happens because at the start of operation (when people go to bed at night), heat and moisture accumulated from the day is at its maximum value and the cooling load is at its highest at this point. In such circumstances, a user will usually set the temperature at lower than necessary, hoping for fast cooling. However, heat is removed gradually, and the rate of removal depends on the power of the unit and the Coefficient of Performance (COP) of the air conditioning units. A long period of lowering of internal temperature is likely to happen especially if a unit is undersized. As a result, the temperature in the early morning tends to get much colder than at the beginning of operation. This problem maybe accentuated by the fact that as people sleep, their metabolic rate gets lower over time, and their sensitivity to cold sensation increases even if there is no change in air temperature.

Secondly, the introduction of air-conditioners creates a demand in the consumer market for comforter type blankets (or quilts), the kind of covering used in colder climates. Prior to the introduction of air-conditioners in homes, the use of this blanket type did not exist in Malaysia, except perhaps among the tea planters community living in the highlands, where the weather resembles that of temperate climates during spring or autumn. Nowadays, however, the sale of this type of blanket can be found in abundance in every major retail outlet in Malaysia.

These two factors indicate that overcooling occurs during the night in houses where air-conditioners are used and warrants further investigation. The implication of these factors on the energy demand needs to be studied for a better evaluation and prediction of energy consumption resulting from the use of air-conditioners in homes. This information will also be beneficial for engineers to identify areas of improvement for the design of air-conditioners for home use, both for reducing energy consumption and for delivering satisfactory comfort conditions. The general public would also benefit from a better understanding of the actual problems, and from identifying possible actions to overcome these problems.

1.2 Research objectives

As discussed above, a review of thermal comfort studies in Malaysian homes and on the general use of air-conditioning units reveals little information. The main objective of the research is to obtain a clearer picture of the use of air-conditioners in Malaysian homes. The areas of investigation covered by the study are the environmental conditions, thermal comfort and user behaviour in the use of air conditioning. Information on these issues is further analysed to cover other aspects of air conditioning use, e.g. thermal performance, areas of improvement in design and energy saving potential.

1.3 Research questions

In order to achieve the above stated objectives, the investigation focuses on several key questions:

1. What are the typical environmental conditions found in air-conditioned bedrooms during night time occupancy?
2. How do occupants operate their air conditioning units?
3. What is their adaptive behaviour in achieving comfort during night time occupancy?
4. What is the range of thermal conditions within which occupants should find thermal comfort in an air-conditioned bedroom during night time occupancy?

These questions will be the basis for the investigations carried out in this study and are explained in detail in Chapter 6.

1.4 Aims of study

The study has the following aims with regard to the use of air-conditioners in Malaysian homes:

- To gain an understanding of the desirable environmental conditions and the comfort conditions for night time occupancy of an air-conditioned bedroom.
- Establishment of the neutral temperature, as well as the comfort range, for air-conditioned homes during night time occupancy (The result may be added to the ASHRAE RP884 global database of field surveys in thermal comfort).
- Identification of problems with the existing design of air conditioning units for domestic use.
- To understand the implication of occupants' behaviour, especially the effect of blanket covering thickness used during sleeping, on the resulting cooling energy demand.

1.5 Methodology

Little information on the use of air conditioning in Malaysian homes can be found from available literature. Important information such as the type of units, the type of spaces being air-conditioned and the pattern of use are not available. Due to the necessity of this information for the current study, a preliminary study was conducted. The establishment of this information is needed to provide a structural framework for the main investigation. Following this, a thermal comfort field survey was conducted on selected households. A brief explanation of the two studies follows.

1.5.1 Preliminary study

Two types of investigation were conducted in this study. A general household survey was conducted first, followed by monitoring of internal conditions of air-conditioned bedrooms over several days. The information established during this stage provides the framework and the working parameters for detailed investigation in the main study. Following the analysis of the data gathered in the preliminary studies, the methodology for the main thermal comfort field study was formulated and a more detailed investigation was conducted.

The preliminary studies established two important findings regarding the use of air-conditioners in Malaysian homes. First, the majority of the air-conditioned spaces are bedrooms. Secondly, the periods during which the air-conditioners are used are mainly night time. The subsequent thermal comfort field survey then focused on these two areas of investigations. First, the study focused on the use of air-conditioners in the bedrooms; secondly, the monitoring was conducted during night time.

1.5.2 Thermal comfort field survey

From the preliminary studies, the focus of investigation for the main study is identified. A thermal comfort field survey was chosen as the approach for this study. The survey was conducted on selected households. The thermal comfort field survey adopted the adaptive theory of thermal comfort. This approach assumes that a human is not a static receptive subject in a thermal situation; but that he would adapt, to achieve comfort in a given condition [13]. As such; comfort standards need to be established according to geographical, climatic and even building use type for every case. The methodology of this type of investigation is further discussed in detail in Chapter 6.

1.6 Scope of Study

The focus of the study is limited only to thermal comfort in air-conditioned bedrooms during night time occupancy. This section explains the scope of investigation chosen for the study.

1.6.1 Geographical location

With Kuala Lumpur being the capital of the nation, the region surrounding this city is the most densely populated in Malaysia, accommodating 25% of the nation's 20 million population [1]. The households selected for the study are in Klang Valley, an area within a 25km radius of Kuala Lumpur (Figure 1-1). Apart from Kuala Lumpur, there are a few satellite towns included in this region. At the moment it is not the intention of the study to generalise the findings to the whole of the country. Even though the difference in climatic conditions between other big cities in Malaysia is not significant, it can be argued that separate studies are needed for other cities of different regions to account for possible climatic variations.

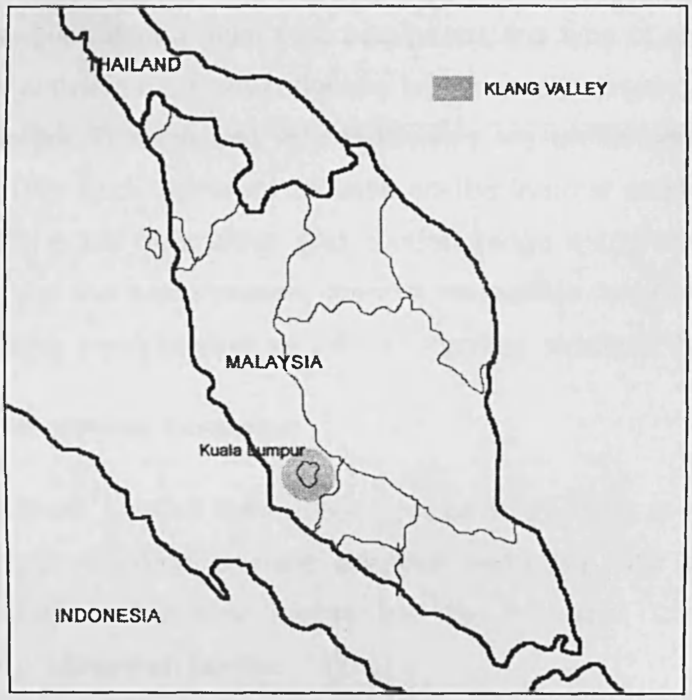

Figure 1-1: Map of Malaysia with the location of study in circle (25km radius around Kuala Lumpur)

1.6.2 Night time study and sleeping activity

A thermal comfort field study is context specific. As such the study has to take into account daily and seasonal variations, building type and activity levels of occupants [14-16]. Normally for seasonal variations, separate studies during winter and summer are necessary. However, in the Malaysian context, there is no obvious seasonal difference in average temperature throughout the year. Analysis of weather data for 2004 reveals that standard deviation for daily average temperature for the year is only 0.9°C[1].

Since the building type under investigation is residential, the period of occupancy can be 24 hours. As such the need to investigate the difference between night time and daytime occupancy is more important than seasonal difference. However, results from preliminary studies (Chapter 7) reveal that air conditioners are predominantly installed in the bedrooms, and used mostly during night time. Hence it was decided that the study should focus on the thermal comfort in bedrooms during night time occupancy.

An important variable in thermal comfort study is the metabolic rate, or the activity level of subjects. Even during night time occupancy, the type of activities in homes ranges from very active to the most sedentary type, namely sleeping. The preliminary studies (see Chapter 7) show that air-conditioners are predominantly used during sleeping hours. This study therefore focuses on the thermal comfort of a sleeping subject, and the thermal neutralities and comfort range established relate only to sleeping activity. For the same reason, thermal neutralities for other type of activity during the occupancy period cannot be inferred from the results of this study.

1.6.3 Range of adaptive behaviour

On top of thermal comfort information, the understanding of the behaviour of people using air conditioning and the adaptive measures they adopt to achieve comfort, will provide a valuable insight into the problems and issues of air-conditioning use in Malaysian homes.

Adaptive measures available for occupants in a domestic situation include numerous options, from changing activity to moving between spaces. In the context of the study, the adaptive behaviour investigated is limited to the actions taken by occupants of the air-conditioned space; in their efforts to achieve comfort between the time they go to bed and the time they get up in the morning. For the purpose specific to the current study, the types of behaviours of concern are limited to:

1. The operational characteristics of cooling appliances, namely the air conditioning unit and auxiliary forced convection such as ceiling or table fan, as used by occupants.

[1] Value derived from weather data from Malaysian Weather Department 2004

2. The personal adaptation of each occupant, i.e. clothing ensemble, and the use of blankets.

An important adaptive opportunity identified in other field studies, namely opening and closing of windows, is not available in the current context, since in the study context, windows are never opened during sleeping hours mainly for two reasons, first is the need to avoid mosquitoes entering the house, secondly for privacy measures. The use of mosquito net will only prevent mosquito during sleeping in the bed, while the need to avoid mosquito is necessary for the whole house during night time. The use of insects screen on windows is not widely practiced in Malaysia even though this product has been on the market for a long time.

1.7 Layout of thesis

The subsequent chapters presented in the thesis are organised in the following way:

Chapter 2 Thermal comfort explains the various concepts and approaches to thermal comfort studies in general. A discussion on the differences between climate chamber studies and field studies, and the corresponding heat balance model and adaptive approach in thermal comfort is given. The international standards for thermal comfort are also discussed.

Chapter 3 Thermal Comfort Field survey looks into the approach adopted in the field survey, since this is the mode of investigation used in the current study. Firstly the development of thermal comfort field study and its contributions to thermal comfort knowledge are investigated. Following this, the method of conducting such a field survey is investigated in detail. This information is then used to formulate the methodological framework used in this study.

Chapter 4 Thermal comfort in Malaysia looks at thermal comfort in Malaysia in general. First the climatic condition of Malaysia is discussed. Several studies on thermal comfort in the tropics are looked into to give a background picture of the region. Several studies on thermal comfort, both climate chamber and field surveys are then investigated.

Chapter 5 Environmental design of Malaysian Housing and domestic air-conditioners discusses the environmental performance and construction of houses in Malaysia. The study looks at the typology of houses investigated in this study. A discussion on the traditional house is also presented to give a good contrast in the environmental design strategy of these houses. Several studies conducted on the thermal performance of some of these houses are presented as well. The use of air-conditioning in Malaysian homes is also investigated from available literature. Firstly, the national energy impact from their use is investigated. Following this, several studies on the use of air-conditioning are looked into to have an understanding of the issues involved in air-conditioning use in homes.

In Chapter 6 Research method, Methodology, the methodology, procedures and techniques of data acquisition and analysis of data for the study are presented. Two levels of investigations are carried out, preliminary surveys and a thermal comfort field survey

A series of preliminary studies were conducted to provide a structural framework for the main investigation. The findings of these studies are discussed in Chapter 7: Preliminary studies- general survey and monitoring. The studies conducted for this purpose were a general household survey and a longitudinal monitoring survey of internal conditions. The findings of these studies established the scope for the main study; that is the use of air-conditioners in bedrooms, and the time of use, i.e. night time.

The results of the main field survey study are discussed in two separate chapters. Chapter 8 environmental condition and occupants' behaviour discusses the findings from the analysis of environmental conditions of the monitored household. The operational characteristics of air-conditioning units and auxiliary fans are discussed to give an overall picture of use pattern and their relationship with environmental parameters. Occupants' behaviour in terms of blanket choice, on top of operating cooling appliances is also discussed.

Thermal comfort analyses using votes cast and environmental parameters are conducted in Chapter 9: Thermal comfort analysis. Several methods of analysis are attempted to establish the neutral temperature for the sample population.

A simulation study was conducted to assess the energy requirements between different comfort scenarios. The differences in energy requirement for an air conditioned bedroom where occupants use normal blankets and those where comforters are used are predicted. The results are discussed in Chapter 10: Simulation study.

There are various problems and restrictions faced by the study that affect the accuracy of the results and applicability of the findings to the wider population. These are discussed in Chapter _11: Limitations of study_,

The findings of the whole study are summarised and discussed further in _Chapter 12: Summary and Conclusions_. Suggestions and recommendation for further investigations and works are also discussed in this chapter.

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2 Thermal Comfort models and developments

2.0 Introduction

At present, the widely accepted definition of thermal comfort is defined in ISO 7730 [1]: "that condition of mind which expresses satisfaction with the thermal environment". Some of the environmental factors affecting the comfort sensation are air temperature, relative humidity, mean radiant temperature and air speed. As such, assessment of thermal comfort is complex. Since the turn of the last century, several attempts have been made to establish a satisfactory working model of thermal comfort. This chapter examines the overall developments of thermal comfort concepts and models.

First the two main methods of investigation in thermal comfort study are explained; following this a brief development of various models is given. However, the details of these developments, which would only form the background to the present study, are not discussed here as they can be found in the literature. An expanded discussion on Fanger's [2] model is given, as it has become the basis for current established methods for assessing comfort worldwide. Following this, the development of the adaptive approach to thermal comfort is presented. This approach to thermal comfort seeks to address some of the problems inherent in the steady-state model developed by Fanger, and eventually provides the theoretical and methodological framework within which the current study proceeds.

2.1 Conceptual terminologies

In the literature of thermal comfort studies, several terminologies are frequently mentioned and commonly found. It is necessary to clarify the concepts behind these terminologies at the outset of the discussion.

2.1.1 Thermal vote

In thermal comfort studies, the subjective sensation experienced by an occupant can be measured by the vote cast on a Likert scale. The most common scale used is the ASHRAE scale, a seven-point thermal sensation scale, which has been used by Fanger [2] and subsequently used in ISO standards regarding thermal comfort (ISO 7730). The scale assigns the value of zero for the neutral sensation, whilst hot being given a value of +3 and cold a value of –3. There are other scales used by other researchers. Another example is the Bedford scale [3]. Even though it is also a seven point symmetrical scale, the denomination assigned for each value is different. This is discussed further in section 2.1.4 below

2.1.2 Thermal Neutrality

In thermal comfort study, thermal neutrality can be described as the thermal condition in which a subject expresses neither warm nor cold sensation. In the seven-point comfort scale, this is the temperature that corresponds to the zero vote. A scientific definition of thermal neutrality can be found in the Glossary of the American Meteorological Society:

"The condition in which the thermal environment of a homeothermic animal is such that its heat production (metabolism) is not increased either by cold stress or heat stress". [4]

It goes on to define the neutral temperature range for a naked human, which is between 29°–31°C (84°–88°F).

2.1.3 Thermal acceptability

Thermal acceptability describes the thermal conditions, which a significant number of people would describe as acceptable. As such, it is described in terms of a range of conditions rather than a specific value. Normally, this is expressed as a lower and a higher value of a thermal sensation scale.

The range of sensation that can be considered as thermally acceptable varies. It has been generally assumed that the three central categories of the 7-point thermal sensation scale (i.e. slightly cool (-1), ok (0) and slightly warm (1)) as acceptable [5]. In ASHRAE RP-884, the adaptive model of thermal acceptability is specified, on the seven point scale, as between -1.5 (slightly cool to cool) and +1.5 (slightly warm to warm) [5]. This is illustrated more clearly in Table 2-1. On the other hand ASHRAE standards 55 [6] specify three ranges of acceptability and it is discussed in more detail in section 2.4.2.

2.1.4 Thermal preference

Another concept in subjective assessment of comfort focuses on the issue of thermal preference, introduced by McIntyre [7]. This scale identifies the thermal conditions people prefer to be in rather than the exact sensation they are experiencing. The neutral vote is categorised as 'no change' whilst the other two are 'want cooler' and 'want warmer'.

Although there are semantic differences between the scales above, de Dear [5] argued that the difference is not significant. The relationship between the different scales discussed above is shown below:

Table 2-1: Common rating scales used in comfort research in the field (source: [5])

	ASHRAE scale	Bedford scale	Acceptability	Preference (McIntyre)
3	hot	much too warm		
2	warm	too warm	unacceptable	want cooler
1	slightly warm	comfortably warm		
0	neutral	comfortable	acceptable	no change
-1	slightly cool	comfortably cool		
-2	cool	too cool	unacceptable	want warmer
-3	cold	much too cool		

Having established the definition of these concepts, the discussion can now focus on the development of various models. To understand these models, it is necessary to recognise the main type of investigative techniques used in thermal comfort study. The discussion on these techniques is discussed in the following section

2.2 *Investigation methods*

Thermal comfort models discussed in the following section can roughly be distinguished by two schools of thought, i.e. heat balance models and adaptive models. The differences between the two can partly be attributed to the differences in their investigative techniques. Steady state models are developed by climate chamber studies, while adaptive models rely on findings from field studies. The distinctions between the two methods of thermal comfort studies are discussed briefly in this section.

2.2.1 Climate Chamber studies

In this type of investigation, subjects are placed inside a climate-controlled chamber. Environmental parameters within the chamber can be controlled by mechanical means to achieve the intended values for investigation. Subjects are normally told to wear a certain level of clothing and maintain a certain level of activity. Then they will cast their votes of their thermal experience on a scale to indicate their psychological assessment of the environment. The main advantage of this method is that a high degree of control of various parameters is possible, and a thorough investigation of the relationship between the parameters can be conducted. A universal model can thus be produced to be applied to other situations. An example of this is Fanger's PMV model which is discussed further in section 2.3.2.

2.2.2 Field surveys

In this type of study, the environmental conditions of real buildings or spaces are measured, taking into account daily, seasonal or climatic variation, while the responses of people in-action in the occupied spaces are studied. The main advantage of this method is the inclusion of the dynamics of real life conditions of an occupied space under investigation, hence this is deemed more valid for specific situations. However the drawback of this method is the uncertainty factor due to lack of control of the parameters. As such, the validity of findings from field surveys is limited to similar situations only. This means that separate surveys are needed for different building typologies, different climatic conditions, different activities, and different geographical locations.

2.3 Thermal comfort models

For clarity, a thermal comfort model can be defined as a working framework explaining the relationship between several parameters affecting thermal comfort. This section discusses the development of thermal comfort models. Some early indices are presented first, each described in brief. Following this, an elaborate discussion on a model developed by Fanger in the 1970s is given.

2.3.1 Early Thermal comfort indices

As mentioned earlier, thermal comfort is influenced by more than one factor. There have been several attempts by researchers to produce a unified means of assessing thermal comfort by taking into account some or all of these factors into a single index.

Houghton and Yagloglou conducted a series of studies on behalf of ASHVE in the USA in 1923 [8], which led to the development of Effective Temperature (ET) index. The ET index uses the concept of a standard environment as the basis for evaluation. One of the standard conditions is that the air is still and saturated. The effective temperature is then the temperature that would give the same thermal sensation in the standard environment as the sensation in the actual environment.

However, only two levels of clothing were considered. One for persons stripped to the waist (Basic Effective Temperature) and another for normally clad persons (Normal Effective Temperature).

Vernon and Wagner introduced the use of a globe thermometer in ET in order to take radiant heat into account, which led to the development of Corrected Effective temperature (CET)[9]. In France, Missenard introduced the concept of resultant temperature by the use of wet globe and dry globe temperature [10] to mimic the physiological response of a human.

In another attempt to mimic the response of a human body, Dufton introduced the use of a heated black copper cylinder, known as eupatheoscope[2] [11]. Bedford used this thermometer to investigate the relation between thermal parameters and personal sensations of factory workers [3]. Using the data, he developed the equation for equivalent temperature index, which takes into account air temperature, mean radiant temperature, humidity level and air speed.

The indices discussed above is summarised in Table 2-2. It can be seen from the above that there is no one index which has the versatility to cater for the complexity of thermal comfort assessment in various real life situations, without assuming a standard value of at least one or two contributing factors. The lack of a versatile model means the task of establishing and assessing thermal comfort cannot be mandated for universal application.

Table 2-2 Summary of some early indices of thermal comfort

Indices	Authors/researchers	Description
Effective temperature	Houghton and Yagloulou (1923)	combining air temperature, relative humidity and air movement into a single scale of temperature. However the use of this scale is restricted only to two clothing levels, part clothed and 'normal' clothed subjects
Corrected effective temperature	Vernon and Warner (1933)	Inclusion of radiation by means of globe temperature in place of dry bulb
Equivalent temperature	Dufton (1929)	Based on the eupatheoscope[2]. Taking into account air & mean radiant temperature, air movement and but excluding humidity
Resultant temperature	Missenard (1935)	Effective temperature with radiant component.
Equivalent temperature index	Bedford (1936)	Based on field observations and analysed statistically

[2]It consists of a blackened hollow copper cylinder heated by a carbon filament and a metal filament lamp, which are controlled by a thermostat to maintain a temperature of 75°F.

2.3.2 Fanger's model: PMV-PPD

A significant contribution in the field of thermal comfort study was done by Fanger in 1970 [12]. In his work, Fanger developed a practical method of assessing the thermal comfort of a given environmental condition. In his comfort model, he included, on top of the environmental variables, two personal factors; activity level and clothing insulation level.

The comfort equation developed by Fanger was achieved by conducting multiple regression analysis of all the parameters against the vote for comfort cast by subjects in a climate chamber test. The experiment was based on several American experiments in the 60's whereby college-age subjects were exposed to three hours of uniform environments [13]. In his work, Fanger used 128 Danish college-age subjects and 128 Danish elderly subjects.

One of the conditions for the development of Fanger's model is the need to have a steady state condition where the environmental condition does not fluctuate. Subjects were put in the climate chamber for three hours and asked to cast their vote at every half hour. To exclude the possible error of different metabolic rate effect due to previous activity, only the last three votes were used in the analysis.

The equation developed by Fanger, known as the comfort equation, can be used to predict the average sensation vote as would be cast by a population in a given thermal environment. Predicted Mean Vote (PMV), the term coined for the method, has been adopted by International Organisation for Standards and become the basis for determining comfort in its ISO 7730 document.

For practical purposes, Predicted Percentage Dissatisfied (PPD) is used, as a derivative of PMV to evaluate the general discomfort of a given situation, as it is more likely for a group of people to express discomfort than mentioning how comfortable they are. The equation for PPD is shown below. The relationship is shown in chart format in Figure 2-1:

$$\mathbf{PPD = 100\text{-}95exp[0.03353 \times PMV^4 - 0.2179 \times PMV^2]}$$

Equation 2-1

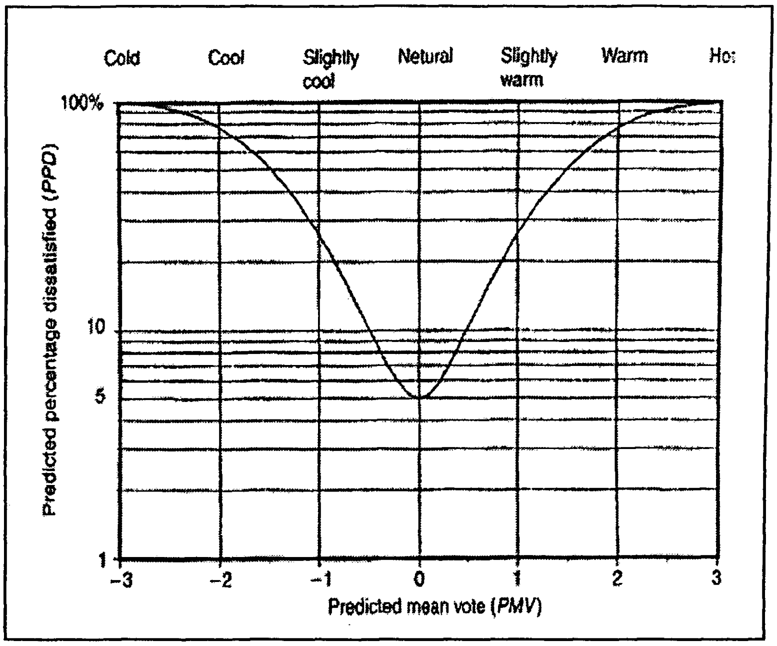

Figure 2-1: The predicted percentage dissatisfied as a function of predicted mean vote (PMV) index.

From the chart it can be seen that even at vote 0 produced by PMV calculation, it is predicted that around 5% of the population would not express satisfaction. This is due to the fact that comfort sensation is also dependent on other psychological and physiological factors on top of the six parameters of thermal comfort.

Fanger analysed the results between the different populations in his sample and by comparing the results with the works by Nevins [13], he concluded in his findings that the equation can be used regardless of geographic location, age, sex, body build and ethnic origin.

Even though both experiments were conducted in temperate climate, Fanger proposed that PMV can be used for the tropics by applying the method on the findings of Ellis [14]. In his work, Ellis investigated European and Asian subjects in Singapore and the thermal neutrality established was found to be similar to the value proposed by PMV. Subsequently Fanger summarised other works in tropical climates and compared it with PMV [15]. He concluded that PMV could be used effectively in this region.

The only evidence of adaptation from climate chamber experiment comes from Abdulshukor [16]. In his experiment, he used subjects of different climatic and cultural background to see the discrepancies in comfort perception between them. He found that Chinese subjects in a Malaysian climate chamber preferred a temperature of 28.0°C. Malay subjects in a Malaysian climate chamber preferred an even warmer temperature at 28.7°C, while Malay subjects in a London climate chamber study preferred only 25.7°C. This contradicts Fanger's findings by suggesting that climatic adaptation or even cultural background do affect comfort perception on top of the six variables used in Fanger's PMV method.

Nevertheless, the PMV method has been accepted widely as a reliable model for thermal comfort assessment. With the establishment of the PMV-PPD method, it is then practicable to include thermal comfort specifications and assessment procedures in a standard or a guideline. The following section explains the standards for thermal comfort as found in ISO and ASHRAE publications.

2.4 Thermal comfort standards

Two major publications dealing with thermal comfort standards are ISO 7730 and ASHRAE standards 55. This section gives an overview of these standards.

2.4.1 International standard - ISO 7730

The ISO standards regarding the provision of comfort for human occupations are divided into three main areas, i.e. hot, moderate and cold environment. The standards for the ergonomics in hot and cold environment deal with the requirements for extreme thermal conditions. For the purpose of this study, the area of concern is the moderate environment, which is dealt in ISO 7730 (Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort) [1].

ISO 7730 specifies the use of PMV-PPD based on Fanger's work for the determination of comfort. It also establishes criteria for local thermal discomfort due to draughts, based on the works of Olesen [17] and Fanger [18]. It is derived from a heat balance equation for the human body combined with empirically determined equations, which define sweat rates and mean skin temperatures that are within comfort limits.

2.4.2 ASHRAE Standards 55 (2004)

Another set of standards regarding thermal comfort can be found in a publication by American Society of Heating and Refrigerating Engineers (ASHRAE). The standards that deal with thermal comfort are found in ASHRAE Standards 55 - Thermal environmental conditions for human occupancy [19]. This standard specifies conditions in which a majority of occupants will find the environment thermally acceptable. In the standard, a majority is defined as 80% of the occupants exposed to the same conditions within a space. The standard is intended for use in the environmental design and commissioning of buildings and other occupied spaces and their HVAC systems. The standard also specifies the PMV-PPD method for the evaluation of thermal environments.

The standard allows a designer at the outset to decide the level of comfort class to be provided in a space. This will influence the HVAC-system design and possibly the building design. Table 2-3 below shows the description of the three classes of acceptable comfort condition.

Table 2-3 Three classes of acceptable thermal environment for general comfort as specified in ASHRAE Standards 55

Comfort Class	PPD (%)	PMV range
A	<6	-0.2 < PMV < + 0.2
B	<10	-0.5 < PMV < +0.5
C	<15	-0.7 < PMV < +0.7

The establishment of a universal model of thermal comfort enables the assessment of thermal comfort to be mandated in these standards. The reliance of these standards on the PMV-PPD model however raises some criticisms. The following section explains the development of an alternative model of thermal comfort and its subsequent inclusion into ASHRAE standards 55.

2.5 Adaptive approach to thermal comfort

In parallel with climate chamber studies, field studies have been conducted throughout the world with the same objective of determining comfort conditions for various populations. While several field studies seem to agree with the results obtained by using the PMV-PPD method, some studies have found discrepancies with it. Among the explanations for the reasons of this discrepancies offered by researchers conducting field studies is that people in real life have the capability to adapt to achieve comfort that they eventually can be neutral in a wider range of thermal conditions. These adaptations are not accommodated in the development of climate chamber study model. An adaptive approach to thermal comfort was proposed from the results of these field studies. This section discusses the development of the model based on this approach.

2.5.1 Findings from earlier field surveys

Fishman and Pimbert conducted an extensive field study of office workers in the United Kingdom and found that the result seems to concur with the PMV-PPD method [20]. However, the criticism against their field study approach is the use of average metabolic rate (80 W/m2) and a clo value of 0.8 which overlooks the fact that people are free to adjust their clothing and activities in field study investigations [21].

Analysing data from several field surveys, Nicol and Humphreys [22] and Humphreys [23] proposed that the comfort vote correlates with the mean temperature experienced by people. In another study, Humphreys [24] proposed that the comfort temperature actually correlates with the mean outdoor temperature experienced by people. These findings suggest that there are other variables that should be taken into consideration when determining comfort condition, on top of the six used in the PMV model.

De Dear conducted a meta-analysis of a field study database acquired from around the world and compared it with the PMV method [25]. He found that while the PMV seems to predict accurately the comfort temperature for air-conditioned buildings, the same cannot be said of 'free-running' buildings. Figure 2-2 and Figure 2-3 show the difference between PMV prediction and the trend line of field survey observations in centrally air-conditioned buildings and naturally ventilated buildings. It can be seen that in naturally ventilated buildings, the PMV predicts that people will be warmer in high temperature and cooler in low air temperatures than they actually are.

The reason for this discrepancy, as offered by the adaptive model is that, people in free running buildings actually adapt to different temperatures so that they can be comfortable when the temperature gets higher or lower. The range of adaptation found in free running buildings is wider, such as opening or closing windows, operating ceiling fans, turning on local heater or cooling equipment etc. Such adaptation is not possible in centralised HVAC buildings, where the internal condition is strictly controlled by mechanical means. The PMV model does not take this ability to adapt as a factor in determining comfort, and as a result, predicts comfort differently from the findings of the field survey of free running buildings.

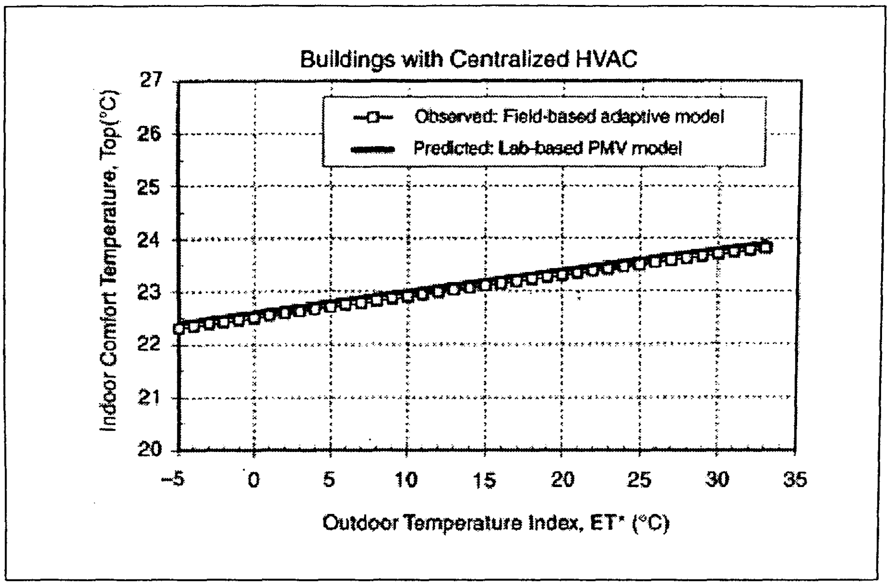

Figure 2-2 Trend lines of Indoor comfort temperature against outdoor temperature index for centrally conditioned building (source [26]

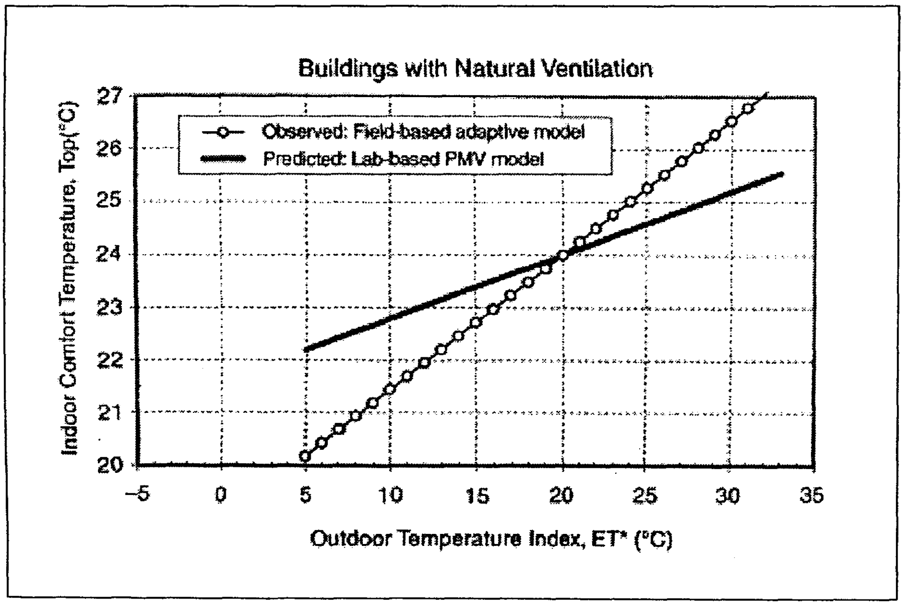

Figure 2-3 Trend lines of Indoor comfort temperature against outdoor temperature index for naturally ventilated building (source [26])

2.5.2 Criticism of the steady state model

As has been discussed above, the findings from field surveys raise questions regarding the universality of the PMV-PPD comfort model. Part of the problem with the PMV-PPD method can be argued within the theoretical foundation of the model itself.

One of the main criticisms with PMV-PPD is the reliance of the model on data collected exclusively from climate chamber investigations. In this kind of study, the data was obtained within a controlled condition which has been set to be at steady level. In real life situations, on the other hand, steady state conditions are the exceptions rather than the norms.

It is also necessary to establish the exact metabolic rate and clothing level for the implementation of PMV-PPD. As it is difficult to predict these values, researchers conducting studies have often resorted to using average values acquired from standard tables. The reliance of the PMV-PPD method on estimated values has often been the subject of debate among researchers. When some of the findings do not tally with empirical data from field survey, the errors are often dismissed as results of inaccuracy of these estimates [21].

The results from field studies suggest that behavioural, cultural, and climatic adaptation change the perception of comfort. Several researchers have attempted to resolve this problem.

Humphreys introduced the concept of the adaptive approach to thermal comfort [27]. The adaptive principle in thermal comfort can be defined as "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" [26]. In this approach, other factors that have an influence on comfort are taken into account, such as local climate, geographical location, building design, occupants' choice of control, clothing and posture.

2.5.3 Some Adaptive Models

The wide range of adaptive actions available for achieving comfort makes it difficult to construct a model that will cater for the effects of various adaptive actions on the neutral temperature of a population. However, several studies had shown that the neutral temperatures for various populations can be simplified on several measurable parameters, such as the ambient internal conditions or outdoor conditions.

Based on a review of 30 buildings in different countries Humphreys [24] proposed that the neutral temperature can be obtained from the monthly mean air or globe temperature:

$$\mathbf{Tn = 11.9 + 0.534T_o}$$

(Equation 2-2)

Where Tn is the neutral temperature (°C) and T_i is the mean air temperature (°C).

On top of the data used by Humphreys, Auliciems [28] added data from other field studies, combining data from naturally ventilated buildings and air-conditioned buildings, a total of 53 separate field studies. Eventually he proposed a single line model which covered both types of buildings. The equation for the model is:

$$T_n = 17.6 + 0.31T_o$$

(Equation 2-3)

Where T_n is the comfort temperature and T_o is the monthly mean of the outdoor temperature.

Nicol and Humphreys [29] produced a regression equation between thermal comfort and outdoor mean monthly temperature which seems to provide a satisfactory model. The equation for comfort proposed is as follows:

$$T_n = 13.5 + 0.54T_o$$

(Equation 2-4)

Several other researchers have also adopted the use of mean monthly outdoor temperature as a regression component. [30-32].

The reliance of these models on outdoor conditions is further examined by Humphreys [33] and Nicol [34]. They suggest the use of an exponentially weighted running mean outdoor temperature which takes into account the daily mean temperature of the last day and the previous days with decreasing weighting factors. They argued that this model gives more accurate results, as it takes into account people's previous experience with the climate.

Parsons [21] however, considered that the use of the outdoor conditions as a determinant for internal comfort temperature lacks the sophistication and contribution to understanding of thermal comfort that a truly behavioural or adaptive paradigm could offer. He believes that the range of adaptation not only happens due to differences in climatic conditions, but that other social, behavioural and cultural factors also play important roles in the adaptive responses of occupants in achieving thermal comfort. Nicol [29] however, argued that peoples clothing insulation and the use of building control is a function of outdoor climate. Hence he argues that the intricate relationship can be treated as an 'empirical black box' which simplifies the relationship to between comfort and the outdoor climate.

Nevertheless, the adaptive actions taken by people are interesting to examine. Within the same climate, the variation due to this behaviour may further shed light on socio-cultural or behavioural effect on comfort perceptions. Various categories of adaptation are discussed in the next section.

2.5.4 Categories of adaptation

It is necessary to establish what constitutes an act of adaptation. de Dear [5] identified three broad categories of adaptation that will help the understanding and analysis of thermal comfort studies. They are:

1. Behavioural adjustment : can be further classified into three subcategories-
    a. Personal adjustment – This includes modification to personal variables such as clothing, posture, activity level etc.
    b. Technological/environmental adjustment – modifications of the environment, e.g. turning on cooling/heating appliances, increasing ventilation or air movement by fans or opening windows.
    c. Cultural adjustments: for example shifting work/rest time, putting on appropriate dress code for certain occasions etc.
2. Physiological: concerns with the changes in physiological responses resulting from exposure to environmental stressors. Over time, the strain induced by such exposure is reduced. This type of adaptation can further be broken down into two subcategories:
    a. Genetic adaptation: Such adaptation is hereditary and takes place over several lifetimes of a group of people.
    b. Acclimatisation: Changes in the setting of one's thermoregulation system over a period of days or weeks, in response to exposure to environmental changes.
3. Psychological: This adaptation refers to the changes in perception and reaction to thermal experience. It includes personal experiences and expectations of the internal conditions. As such this type of adaptation varies between different times and conditions, even within a single individual. For example, a person on a golf course in the tropics can tolerate higher temperature than when he is inside an air conditioned building.

Physiological adaptation, relates to the acclimatisation of subjects with the local climate, and as such its effect can only be practically tested by investigating the difference in thermal sensation of subjects when they move from one climatic zone to another, and studied over period of days or weeks. Assuming the percentage of population doing this on regular basis is small, the effect of this adaptation on the thermal sensation of a population is negligible. While psychological adaptations do effect the thermal perception, it is assumed that subjects sleeping in an air conditioned room have similar psychological expectation of their thermal conditions; hence the effect of this type of adaptation on thermal perception of a population can be assumed insignificant. Behavioural adaptation has the most direct influence and can be ascertained by identifying differences in thermal neutralities between different behaviour. Hence, this type of adaptation is the focus of the current study.

2.6 Thermal comfort for sleeping subjects

The current study investigates the thermal comfort of people during night time occupancy of an air conditioned bedrooms using field survey techniques. The thermal analysis is restricted to that data relating to subjects when they are at sleeping metabolic rate (0.7). It is possible to use the PMV method to establish the thermal comfort of the study population. However, the study opted for a field survey to establish this information, and as argued later, the PMV method cannot be reliably applied on the data gathered in this study (see discussion in Chapter 6).

Thus a theoretical problem arises from this approach. Since sleeping people cannot be asked to cast vote, it would not be possible to establish a field survey thermal analysis on any sleeping subject. However, the study takes the stand that within a few minutes of waking up, people's metabolic rate are similar to that of a sleeping person. Hence, any vote cast by subjects the moment they wake up is taken as that of a sleeping person.

Another difficulty faced by the study is in comparing the results with a similar study. None of the field surveys in the literature reviewed relates to sleeping activity. However, comparison with the adaptive comfort models discussed in 2.5.3 is possible since these models did not specify activity level, but rather general comfort requirement. Comparison with other field studies is nevertheless conducted to evaluate the general agreement of the thermal neutralities with other findings.

2.7 Summary

This chapter investigates the various concepts and models of thermal comfort. Thermal comfort investigations fall into two major schools of thought, those based on climate chamber studies and those based from field surveys. The findings of climate chamber studies led to the development of the PMV-PPD method of thermal comfort evaluation. While the PMV-PPD method provides the establishment of methods widely used in international standards, a growing number of field studies show some inconsistency with the condition proposed by this method. An adaptive approach to thermal comfort has been proposed to provide an alternative to the PMV-PPD method. The adaptive approach to thermal comfort proposes the establishment of comfort conditions by taking into account contextual factors such as geographical locations, climatic conditions and adaptive behaviour of occupants. A more reliable model is to consider the effect of local climate as a contributing factor in determining comfort temperature. This suggests that, for the evaluation of thermal comfort, a field study is needed for different climatic conditions. The two groups of thermal comfort models, i.e. steady state model and adaptive models differ in the manner in which the investigation methods are conducted. For steady state models, the investigation technique used is a climate chamber study. Adaptive models, on the other hand, are derived mainly from field survey investigation. In the next chapter, a discussion on a suitable type of thermal comfort investigation method for the current study will be conducted.

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3 Thermal Comfort Field Surveys

3.0 Introduction

This chapter discusses the method of investigation adopted for this study. First, the justification for the adoption of the field survey method for the current study is explained. Following this, the development of thermal comfort field studies is explored and the common practices and methodology in field studies are investigated. The discussions will form the framework within which the current work proceeds.

3.1 Adoption of the adaptive model and field survey methodology

The current work focuses on the comfort condition of air-conditioned bedrooms during night time occupancy in Malaysia, and the occupants' behaviour in these spaces. This poses several methodological restrictions, which tend to be more suitably handled by field survey method rather than a climate chamber. The arguments for the adaptive model and field survey methodology are further presented below.

3.1.1 Variations in insulation levels

One of the problems in the current study is the uncertainty in insulation levels and metabolic levels. People vary in their clothing whilst at home. The uncertainty of insulation values is further complicated by the fact that people have the choice of using blankets of various thicknesses, with varying degrees of use and at different points in time. While the steady state model requires the assumption of fixed clothing levels and activity levels, the black box approach used in adaptive models (discussed further in section 3.2 below) allows for this variation of insulation levels but is averaged across many subjects.

3.1.2 Dynamic thermal conditions

A prerequisite of a climate chamber study is the condition of steady state, where the thermal conditions investigated must be maintained for a stipulated length of time before any psychological measurement can be taken. Although the use of air-conditioners may theoretically provide a stable condition, their pattern of use will eventually determine the resulting thermal conditions. A user may choose to switch on or switch off an air-conditioner several times during an occupancy period. He may further carry out adjustment to the temperature setting or even the blower settings of the unit. In a domestic situation, it is also possible that the internal conditions are influenced by the ambient external condition, which typically gets colder towards morning. As such, an initial assumption can be made here that it is unlikely for the internal thermal conditions to achieve a steady state. The data obtained from the preliminary investigation (discussed in Chapter 6) confirms this scenario. It is found that the thermal conditions of an air-conditioned bedroom hardly fall into a steady state condition.

3.1.3 Free running typology

As had been discussed in Chapter 2, a heat-balance model is more successful in predicting the thermal comfort of occupants of a climate controlled building compared to a free running building. Although the study focuses on air-conditioned bedrooms, the building type for these spaces can be considered as 'free running' for several reasons discussed here. Firstly, the decisive criteria in the classification of the building type as a free running building is the opportunity for the occupants to alter any of the six factors to achieve the desired comfort conditions. De Dear [1] defined a free running building as one which offers an opportunity for the occupants to at least have control over an openable window. In the current study, users have great control of the internal conditions by choosing the pattern of use of air-conditioners to suit their needs. The definition of a climate controlled building, on the other hand is more suited to buildings with centralised air-conditioning.

The categorisation of a domestic space as a free running building has a significant implication in the choice of a suitable model for investigation. de Dear [2] demonstrated that in a 'free running' building, the inaccuracy of the PMV-PPD method is more pronounced. Hence, the use of the adaptive model is more appropriate.

From the discussions above, it can be argued that the use of adaptive models and the field survey method is more suitable for the purpose of this study. The following section discusses the development and the techniques used in thermal comfort field surveys.

3.2 Development of thermal comfort field surveys.

In field surveys, various parameters cannot always be determined (e.g. clothing value, metabolic activities, postures, building conditions, etc.) As such, the effort to develop a standard formula, incorporating all the parameters from field surveys is difficult. One way of overcoming this problem is to a treat the problem as a 'black box' case where the relationships between various variables to achieve comfort are ignored, while only the results are acquired [3]. This means for every case, a field study needs to be conducted to ascertain the thermal comfort requirement for a particular context. With this purpose ASHRAE collaborated with Macquarie University, Australia, to conduct a massive worldwide project, incorporating data from various field studies [1]. The description of this project is conducted in the next section.

Among the early work in field studies was that conducted by Bedford in 1936 [4] who conducted a survey among British factory workers. To assess the thermal experience, he used a 7-point sensation scale, often known as the 'comfort scale' (see Table 2-1). He conducted some regression analysis using the correlation between several thermal values with the comfort votes. Utilising this data he came up with the concept of equivalent temperature, in which air and radiant temperatures and air velocity are taken into consideration. Other works in Britain were carried out by Black [5], Black and Milroy [6], Langdon and Loudon [7] and Humphreys and Nicol [8].

Other works in various parts of the world was also conducted with interesting results. In 1959, Webb conducted a survey on office workers in Singapore and introduced the concept of equatorial comfort [9]. Sharma and Ali conducted studies among Indian office workers in 1986 and introduced the tropical Summer Index for the determination of comfort conditions in such situations [10].

In Australia, Auliciems and his team studied several homes, colleges and schools [11]. Williamson *et al* conducted field surveys in dwellings in several parts of Australia [12]. Other work was done by Auliciems and de Dear [13]

The American Society of Heating, Refrigerating and Air-conditioning Engineers has sponsored a series of field studies with the objective of evaluating thermal comfort models in its thermal comfort standard ASHRAE 55. Among the studies conducted for this purpose were Schiller *et al* [14], and the ASHRAE research project RP-884 (discussed below) by de Dear and Brager [2].

The reliance of the adaptive model on contextual parameters, such as outdoor conditions suggest that for various climatic conditions or geographical locations, a field survey is needed in each to establish the range of acceptable thermal conditions. It is the objective of this study to fill this gap of information for domestic air-conditioned spaces in Malaysia.

3.3 ASHRAE RP-884

To substantiate their specifications in ASHRAE 55 Standards, ASHRAE has sponsored several field studies [15-17]. These and other similar studies led to the development of the global database of thermal comfort and field surveys [18], codenamed ASHRAE RP-884. The project is a collaboration between ASHRAE and Macquarie University, Sydney. The project collected data from various researchers around the world working on thermal comfort field surveys into a huge global database [19].

The project managed to collect around 22,000 raw data sets from various studies from around the globe. To make these data more streamlined for analysis, they were rated and reformatted into a template for further analysis. The database enables researchers to carry out meta-analysis and a more comprehensive adaptive model and preference is then made possible. [15]. ASHRAE has adopted this finding in its latest version of ASHRAE 55 documents under the section determining comfort conditions for naturally ventilated buildings. Using the adaptive model produced from this study, the standards produced a graphical representation of comfortable comfort range for naturally ventilated buildings, as shown in Figure 3-1 . The comfort range is defined by the shaded area that corresponds to the mean monthly outdoor temperature. The minimum indoor comfort temperature however is 16°C and the maximum is 32°C for 80% people acceptance. The dotted line indicates the narrower range for 90% acceptance. This is among the early example of the adaptive approach being accepted in a thermal comfort standard.

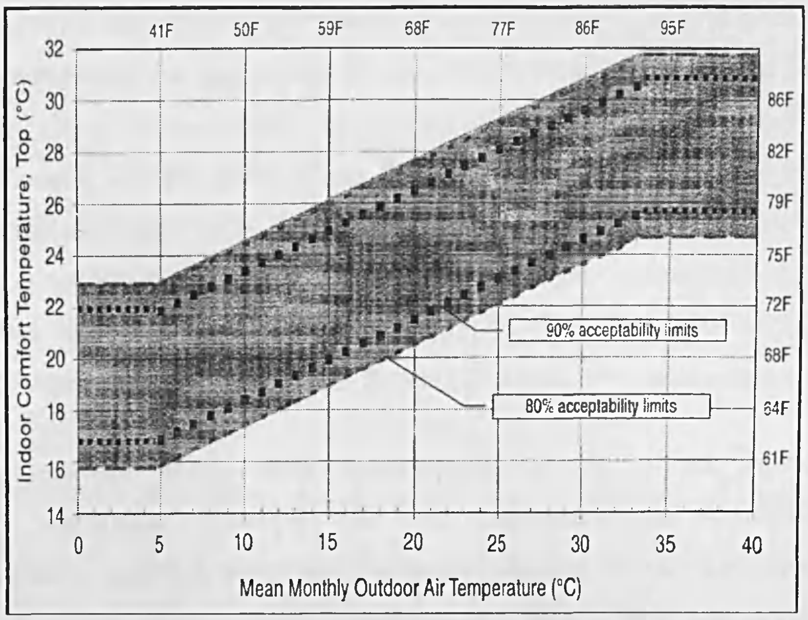

Figure 3-1 Acceptable operative temperature range for naturally conditioned spaces (Source ASHRAE standard 55, 2004)

The datasets acquired in this study has been proposed for inclusion into the ASHRAE RP 884 database. The context of this study, i.e. night time thermal comforts in a domestic setting in hot humid region; will add a new dimension to the database[3].

3.4 Normal practice in field surveys

There was no standard procedure for field surveys in their early development. However, these studies share some common principles and procedures. This section investigates the normal practice of field surveys. The guidelines regarding the methodology for conducting field surveys can be found in ASHRAE standards 55 [20]. Another set of guidelines applicable to the needs of the current study can be found in a publication by Nicol [21]. The procedure discussed herein will form the basis of the investigation method used in this study.

3.4.1 Types of Survey

Field data are classified by ASHRAE according to the standard of instrumentation and procedures used for indoor climatic measurements. For example, ASHRAE RP-884 aggregated the field surveys accumulated in their database into three broad classes of thermal comfort field investigations:

[3] The author had contacted Prof de Dear, the head of the project on this matter in September 2007. He confirmed that it is possible to include the datasets from this study into the database provided that they have been streamlined to the project's database format.

Class I surveys were field experiments in which all sensors and procedures were in 100% compliant with the specifications set out in ASHRAE Standard 55 -1992 [22] and ISO 7730 [23]. In particular, all of the shortcomings identified in Class II investigations were absent from Class I field experiments. These include three heights of measurement with laboratory-grade instrumentation including omni directional anemometry capable of turbulence intensity assessments. ASHRAE-sponsored field experiments in the San Francisco Bay Area (RP-462), Townsville (RP-702) and Montreal (RP- 921) are examples of Class 1 investigations.

Class II surveys were field experiments in which all indoor physical environmental variables necessary for the calculation of Standard Effective Temperature (SET) and PMV/PPD indices were collected at the same time and place as the thermal questionnaires were administered. Not all the measurements may have been made at the three heights above floor level as specified in ASHRAE (1992) and ISO (1994) standards (0.1, 0.6 and 1.2m). Humidity measurements were taken by aspirated psychrometer or solid state hygrometer sensors. Air speeds were measured by hot wire (or sphere) probes with thresholds above 0.1 m/s, directional sensing elements and time constant[4] larger than that necessary for turbulence intensity assessments.

Class III surveys were field studies based on simple measurements of indoor temperature and possibly humidity, with one level of measurement above the floor. The field studies used to derive the previously published adaptive models [24-26] were all Class III.

Nicol [21] divided field studies into three types or "levels" of survey, reflecting the variation in the level of detail of the investigation, as follow;

1. Level 1: Simple measurements of temperature in occupied dwellings.
2. Level 2: Measurements of thermal environments and the subject's response to it
3. Level 3: Surveys that include all six factors of thermal comfort, together with the subject's responses.

[4] The time constant refers to the time required for the hot wire to change its body temperature by 63.2% of a specific temperature span when the measurements are made under zero-power conditions in thermally stable environments.

3.4.2 Sample selection

The concept of the adaptive approach investigation in thermal comfort mentioned in chapter 2 requires the use of subjects who are familiar with the surroundings and the climate [21]. It is also necessary to allow the subjects to behave as they normally would in the selected experiment, such as providing the normal range of available adaptive options, types of clothing and the type of activity they would normally do. This means that the best setting for such a study would be the field itself, people 'in action'.

In thermal comfort studies, the most common way of selecting samples are transverse sampling and longitudinal sampling. In transverse sampling, a whole or large part of the population will give a single or small number of datasets[5]. Nicol argued that since a large number of people or even the whole chosen population is used, any sampling bias is avoided. Using high number of subjects means results can be fairly accurate [21]. This method has been used in a number of surveys[4, 14]. However, he also argued that this method of sampling is inappropriate for the adaptive model, since the measurements are of a different subject for each temperature, whereas the adaptive study aims to investigate the effect of different adaptations on one subject's thermal perception. However for the current study, in examining the effect of occupants' behaviour on thermal comfort in an air conditioned room, it is more reasonable to expect variation in transverse sampling, since the behavioural pattern of use of air conditioner varies between different subjects rather than day to day variation of one subject.

In longitudinal sampling, a large amount of data is obtained from a small number of subjects over a long period of time. Such methods were used in several field studies such as Webb [27], Humphreys and Nicol [8] Sharma and Ali [10]. The advantage of this kind of sampling is that a large datasets can be obtained for a particular group of people. Several kinds of analysis are possible with this approach. For example it is possible to find the difference between individuals, and the effect of different seasons, and hence climatic condition, on comfort sensations.

3.4.3 Size of Sample

The discussion in this section is based on Nicol [21]. There are no strict rules regarding the size of samples that should be obtained. However, the number of

[5] A datasets is a group of all the environmental and personal data corresponding to and including a thermal vote.

datasets and subjects would determine the type of analysis that could be carried out. Sharma and Ali [10] took an average of 280 datasets for each of 18 subjects, over three hot seasons in India, amounting to 5100 datasets. Humphreys and Nicol [8] collected 5349 datasets from 18 subjects, divided over 85 months period. The use of multiple datasets for each subject is to provide comparative analysis of variations within the same subjects, as well as between different subjects.

A large sample is not always necessary. Smaller sets can give useful and statistically significant[6] results. For example, Griffiths [28] conducted a transverse survey of 17 buildings, with a sample population of between 14 and 53. Not being able to conduct reliable regression with the small number of datasets for each building, he worked out the mean comfort temperature for each vote by using an assumed regression slope for the relationship between comfort vote and temperature. Griffiths then went further and using the same technique with his preference scale (he used an ASHRAE scale for his preference as well as his comfort vote) he was able to estimate the mean preferred temperature as well. Further explanation of this method is discussed in section 3.5.3 in this chapter.

3.4.4 Time of day

It is necessary to consider the effect of different times of day on the comfort sensation. The variation between different days and different hours of the day will have a significant influence on adaptive process. Nicol [29] argued that the response of a subject to his environment is also determined by experience of the thermal conditions of previous period. It is therefore necessary to consider the time of the survey and put this into the sampling, if variations between seasons or hour of the day need to be analysed.

3.4.5 Measurements of environmental conditions

There are several guidelines available regarding the process of measuring thermal environments. In *ISO 7726: thermal environment – instruments and methods for measuring physical quantities* [30], no specific instrument is mentioned, only the specification of performance that should be achieved by instruments for each parameter, is given.

[6] Normally significant might be construed as "statistically significant" which is where a p value of <=0.05 means a smaller than 5% chance the finding could have happened by chance. Insignificant is generally taken as being very small and is not the same as "not statistically significant"

ASHRAE Standards 55 [20] gives clear guidelines regarding the procedure of measuring thermal environments in existing buildings. It recommends measurements to be made in occupied zones of the building at locations where the occupants are known to be or are expected to spend their time. Locations of measurements for various parameters are also specified.

Nicol [31] and Sharma and Ali [10] asked their subjects to take the measurements themselves in order to minimize the disruption to their normal pattern of occupancy. However Nicol [21] later pointed out that this type of measurement ran the risk that the subjects would be influenced by their own reading of their environment.

3.5 Methods of analysis for thermal comfort field survey

In field studies, several variables measured at different times are gathered. A dataset for a thermal comfort field study consists of measured environmental variables, activity levels and insulation levels of subjects, and the corresponding thermal experience as voted by subjects at a particular time. In the adaptive approach, also of importance are the ways people use environmental controls, e.g. opening/closing windows, turning on cooling or heating appliances.

3.5.1 Unit of analysis

Data gathered in a field study can be analysed in several ways. At its simplest, all data gathered in a field study is grouped together, comprising results from different buildings, for analysis. Example of this kind of analysis are found in the early field surveys, such as in the work of Humphreys [8] and Auliciems [11].

This approach in analysing field data has the tendency to overlook the variation within the whole data due to differences between different buildings. In his report for ASHRAE Research Project 884, De Dear aggregates the data for single buildings for the purpose of analysis [1]. This approach, he argued,

"..... masks some of the inherent noise involved in a single subject's thermal comfort assessment, while still providing sufficient data points[7] for statistical modeling purposes"[1]

[7] In this text, de Dear used the term data points to describe datasets

3.5.2 Statistical analysis

Various techniques have been used to give a picture of thermal comfort of the investigated conditions. The main objective of the analysis is to establish the range of conditions within which most occupants found 'comfortable' or 'neutral'. Statistical analyses are used to establish the sample's 'neutrality'.

The most common method used in many field survey analyses is to do a regression analysis between the thermal votes over the range of temperatures found. Normally the temperatures are binned into half degree or whole degree steps, and the corresponding mean vote for each bin are used as regression variables. The regression equation produced by regression of mean votes against temperature can be used to predict neutral temperature, i.e. the temperature at which the majority of occupants express neither hot nor cold sensation.

The limitation of this method is in the assumption that thermal sensation is dependent on the environmental conditions and occupants are not adapting. Whereas in the adaptive approach, it is accepted that subjects would react to adapt to changing conditions so as to maximise comfort in several ways [21].

3.5.3 Analysis of small sample- Griffiths Method

In the current study, the minimum number of datasets gathered from a single subject is two. As such, the minimum number of votes for a household is two, i.e. in the case of only one occupant casting his vote at the time of going to bed and the time he wakes up. As such, in many cases, the data is insufficient to produce a reliable regression estimate for neutral temperature.

Griffiths [28] gets around this problem by using an assumed regression slope between comfort vote and temperature. Based on his investigation of several climate chamber studies, he made the assumption that the increase in temperature for each scale point on the comfort scale was 2.33°C on a nine point comfort scale. (This works out at 3°C for each point on a 7-point comfort scale). Adhering to this formula, for each vote, the neutral temperature can be obtained by subtracting 3°C (on a 7-point comfort scale) times the number of scale points above neutral. The equation for this method is thus:

$$T_n = T_a - (T_{sv})3$$

Equation 3-1

Where T_n is the neutral temperature, T_a is the air temperature when the vote was cast and T_{sv} is the actual votes cast by subjects. For each vote then, the neutral temperature can be worked out where the slope crosses the neutral vote (Figure 3-2). By taking the mean of these neutral temperatures, the neutral temperature for a unit of analysis (a building or a household) can be obtained.

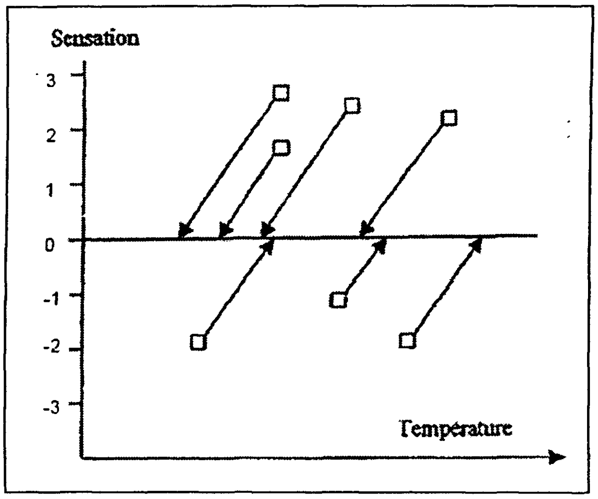

Figure 3-2 Graphical representation of Griffith's method for finding neutral temperature for small samples (*source [21]*)

This method is actually based on the theoretical relationship between comfort parameters obtained in a climate chamber study. Its use in field survey is relatively new but useful, especially for a small sample size study. Humphreys and Nicol [32] had proposed the use of this method on the ASHRAE RP-884 database to ensure that no data are rejected on the grounds of lack of statistical significance. However, de Dear and Brager [33] posit that the use of this method will introduce unnecessary error on the database. Working on the database, they revised the method developed by Griffiths and suggest an increase of 2°C for each point on the 7-point comfort scale. The equation for this method is thus:

$$T_n = T_a - (T_{sv})2$$

Equation 3-2

Bouden and Ghrab [34] used both models on a field study in Tunisia and concludes that even though the method by de Dear and Brager seems more robust, the method by Griffiths is more plausible for low outdoor temperatures, as is the case in their study.

3.6 Summary

The current work focuses on the thermal comfort condition in air-conditioned bedrooms in Malaysian homes. This chapter seeks to identify the suitable thermal comfort model for the purpose of current study. The uncertainty factor in clothing insulation levels of occupants, the non-steady state thermal conditions found and the possibility of the free running nature of these spaces favours the adoption of a field survey investigation method and the adaptive model framework.

Field survey works by others were reviewed. The common practices among these studies are identified with the objective of identifying the methodology for the current investigation. A practical model of an adaptive approach, encompassing all contributing factors mentioned above is still unavailable for inclusion into international standards. However, the latest ASHRAE publication [20] has accepted the use of the adaptive model, which relies on mean monthly outdoor temperature as the basis for determining the comfort range in free running buildings. Several methods of analysing field survey data were also presented. The method to be used in this study will be explained in chapter 6.

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4 Thermal Comfort in Malaysia

4.0 Introduction

This chapter examines the Malaysian climatic conditions and the thermal comfort information available in Malaysia. Firstly the climate of Malaysia is explained. Then, several studies pertaining to regions of similar climatic conditions are also examined. This information will be used to provide comparisons to the findings of the study. Following this, thermal comfort studies conducted in Malaysia, will be explored. The discussion will then focus on studies in the residential sector.

4.1 Climate of Malaysia

Malaysia lies between 1° and 7° N latitude and 100° and 120° E longitude. Kuala Lumpur, the capital city and the location of the study is situated at latitude 3° 8' N and longitude 101° 33'E. Being close to the Equator, the country experiences high temperature and high humidity all year long. This section examines the characteristics of the climate of Malaysia, and the relationship with human comfort.

4.1.1 Wind

Malaysia generally experiences weak wind condition although two major wind systems can be identified. The northeast monsoon starts in November till March, while the southwest monsoon runs from May till September. The period in between these two monsoons are short and characterised by weak wind condition. Stronger wind condition occurs during the Northeast monsoon and characterised by wind velocity ranging from 20 to 40 km/h, although on the exposed east coast it can reach 60 km/h.

4.1.2 Temperature and humidity

Malaysia has a yearly mean temperature of between 26ºC and 27ºC and relative humidity (RH) ranging from 70% to 90% throughout the year with an average of 84% [1]. The Subang Jaya meteorological station (near Kuala Lumpur) recorded maximum daytime temperature between 33ºC to 35.6ºC an minimum night time temperature between 19.6ºC to 22.9ºC [2]. The yearly daily average temperature range is a low 5ºC. Analysis of weather data 2004 and 2005 reveals an average diurnal range of 8.6°C.

Reimann [3] analysed the weather data for Kuala Lumpur and several other locations in Malaysia and produced the distribution of average daily temperature in a typical weather year (Figure 4-1)

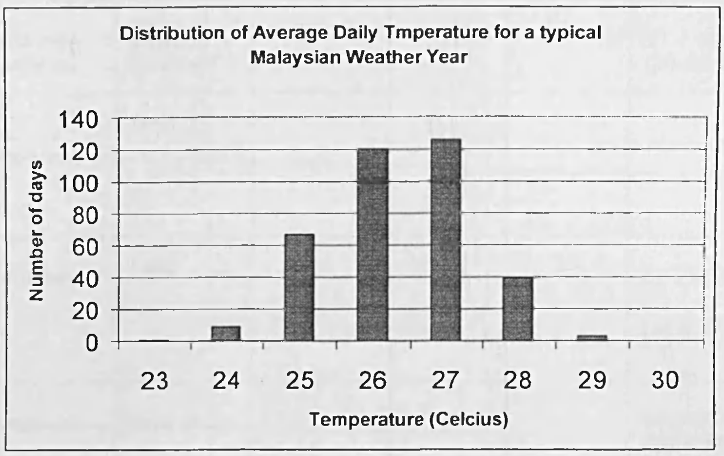


Figure 4-1 Distribution of Average Daily Temperature for A typical Malaysian Weather Year (Source: Reimann 2000)

4.1.3 Climate and human comfort

It is clear from the above that Malaysia experiences uniform high temperature and high humidity throughout the year. Heat and high humidity are the main problems that need to be dealt with in achieving comfort. The high humidity restricts the ability of human physiological adaptation of cooling through perspiration. Sweat cannot easily evaporate in such condition.

In such a climate, Szokolay suggested that cooling through air movement of 1.0 m/s to 1.5 m/s is the best means to achieve comfort [4]. This is consistent with the fact that all household in Malaysia have at least two units of ceiling fans installed [5-7].

4.2 Other thermal comfort studies in the tropics

The climate of Malaysia is similar to several countries in the tropical regions, especially in South-East Asia. Various researchers have conducted thermal comfort studies in these regions. Ahmad and Hyde [8] carried out a review of these studies. The discussions in this section are based on this review. The findings of these studies can provide comparative information for the current investigation and are discussed in this section. Table 4-1 below shows results from some of the studies in Southeast Asia. A discussion on these findings follows.

Table 4-1: Thermal comfort studies in South-east Asia

Researcher	City	Method	Building types	Number of subjects	Relative Humidity (RH%)	Comfort range (°C) DBT	Neutral Temp. (°C)
Mom *et.al.* (1947)	Bandung, Indonesia	Thermal chamber		21		21.7-29.4 (20-26.1ET)	26.0
Ellis (1952)	Journey Singapore to Hong Kong	Field		5211			26.1ET
Ellis (1953)	Singapore	Field		118		22-25.5ET (24.5-27.8 Ta)	
Webb (1959)	Singapore	Field study		16		26.6-30 (25.1-27.3 ET)	26.2 ET
Santosa (1988)	Surabaya, Indonesia	residential					27.4NV
DeDear et. Al. (1991)	Singapore 1	Thermal Chamber		32			25.4
DeDear et. Al. (1991)	Singapore 2	Thermal Chamber		98	70 35		27.6 27.9
Busch (1992)	Bangkok	Field study	Offices (NV 34%, AC 66%)	389 757	50 50 50	22.0-30.5	27.4 ET*(NV) 24.7 ET (AC) 25.0 (all)

Note: NV = Natural ventilated, AC = air-conditioned.

Source: **Ahmad, S.S. and R. Hyde. 2002.**

4.2.1 Climate Chamber Studies

In Indonesia (latitude 6° south), Mom [9] found the comfort (neutral) temperature to be 26°C. In Singapore (latitude 1°20'), de Dear in 1990 conducted climate chamber studies involving 32 college students and found that the comfort temperature was 25.4°C Ta[10]. Another study by de Dear was conducted in the same premises later in the same year involving 98 college students [11]. The upper limit of acceptable comfort zone was 27.6°C T_a at 70% relative humidity and 27.9°C T_a at 35% relative humidity.

4.2.2 Field Studies

The field study conducted by Karyono [12] showed the comfort temperature among office workers in Jakarta was 26.4°C Ta, Comparing this result with the comfort temperature of 26.0°C found by Mom [9], who carried out a similar study in Bandung, Karyono argued that the people in Bandung adapted to lower temperature because of the lower outdoor temperature (by 5°C) compared to the subjects in Jakarta.

In Singapore, field studies were conducted by Ellis [13] and Webb [14] found the comfort (neutral) temperature to be 22°C to 25.5°C ET and 26.2°C ET respectively. Field studies conducted by de Dear in 1990 involved 583 subjects from naturally ventilated apartments and 235 subjects from air-conditioned office buildings. The findings showed that the comfort temperatures were 28.5°C T_o and 24.2°C T_a respectively [15].

Bangkok (latitude 13.7°) has similar outdoor temperature to Jakarta and Kuala Lumpur during its hot and wet season, between March to October. Busch conducted a thermal comfort study during the hot season (April) and the wet season (July) in 1988 involving more than 1100 people [16]. This field study in Thai offices compared two populations, the subjects from naturally ventilated buildings and those from air-conditioned buildings. The study showed that the neutral temperature for naturally ventilated buildings was 27.4 °C ET* while that of air-conditioned buildings, 24.7 °C ET*. The thermal acceptability of all the subjects covers a broad range of 22.0 °C to 30.5 °C, an increase of 4 °C from the upper limit of ASHRAE summer comfort zone. Applying 80% acceptability (percentage of people who vote between -1 and +1 on ASHRAE scale) the author recommended that the upper temperature boundary for comfort should be as high as 31.0°C for naturally ventilated buildings and 28.0°C for air-conditioned buildings instead of the accepted level of 26.1°C.

Karyono [12] made a comparative analysis of all the previous thermal comfort studies done in South East Asia. He concluded that people living in the warm and humid tropical countries prefer similar neutral temperatures, i.e., around 25°C to 30°C. In comparison to the ISO and ASHRAE standards (23°C to 26°C) as shown in Table 3, these figures are 2°C to 4°C higher. He concludes that the higher preferred temperatures seem to be the result of acclimatisation.

These studies in other countries of similar climatic conditions provide a background analysis of the thermal condition expected in the current study. However, it is necessary to note that none of these studies refer to the comfort conditions of night time occupancy in residential buildings.

4.3 Thermal comfort studies in Malaysia

Ahmad and Hyde [8] have also summarised several studies on thermal comfort on various types of buildings and occupancy patterns in Malaysia. Much of the discussions in this section are based on this review.

4.3.1 Thermal comfort standard

Department of Standards Malaysia recommends an indoor design temperature of 24.0°C for non-residential buildings [17], with a comfort range between 23.0°C and 26°C. Currently there is no such recommendation for residential buildings in Malaysia.

4.3.2 Theoretical model

Webb [18] conducted observations on the indoor climate of Malaysia in 1953 and suggested that the comfort range for such condition is between 26.1°C to 27.8°C (mean effective temperature). Abdulrahman [19] proposes that the neutral temperature for Malaysia is 26.7°C for naturally ventilated buildings, 26.2°C for both mixed mode and air-conditioned buildings and 25.5°C for climate controlled buildings at 50% RH and no air movement. Comparing this value with the present recommended indoor design temperature for Malaysian non-residential buildings proposed by the Department of Standards Malaysia [17], i.e. 24.0°C, this neutral temperature for air-conditioned buildings is 1.5°C higher. He further proposed that the presence of air movement (i.e.,1 m/s) can increase the comfort limit even further (up to 33.0°C) [19].

4.3.3 Climate Chamber Studies

Abdulshukor and Young [20] conducted a study on thermal comfort in a controlled climate chamber involving 130 fully acclimatised Malaysian tertiary level students aged 18-24. They concluded that the neutral air temperature for the sample is 28.2°C. The comfort range was found to be between air temperature of 25.0°C and 31.4°C. However the finding of this study has limited application due to the need to limit the values of metabolic activity, clothing insulation and air velocity. All subjects were engaged in light activity of 1.0 met and wore clothes with 0.5 clo values. The air velocity in the chamber was maintained constant at 0.1 m/s and the relative humidity at 50%. Figure 4-2 shows the comfort condition proposed by Abdulshukor and Young.

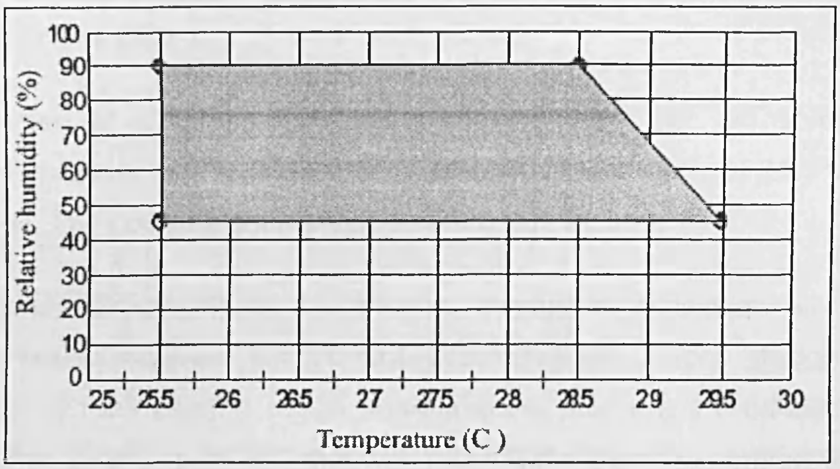


Figure 4-2: Proposed Thermal Comfort Zone for Malaysians in Malaysia (Abdulshukor, Young, 1993).

Zainal [21] conducted a climate chamber study on factory conditions. He concluded that the majority of Malaysians were more tolerant towards higher air temperatures (23°C to 29°C) compared to subjects in the USA and Europe, for example the recommendation by ASHRAE Standard 55 – 1992 for a temperature range for summer season (23°C to 26°C).

4.3.4 Field Studies

Among the earliest work in field studies carried out in the region was one by Ellis in 1953 [13]. He conducted an experimental study on European men and women residing in Singapore and Asians of different ethnic groups. He found that, lightly clad acclimatised Europeans engaged in sedentary occupations were comfortable when the effective temperatures lay between 22.8-25.6°C. The warmth preferred by Asians was higher but the difference was not significant.

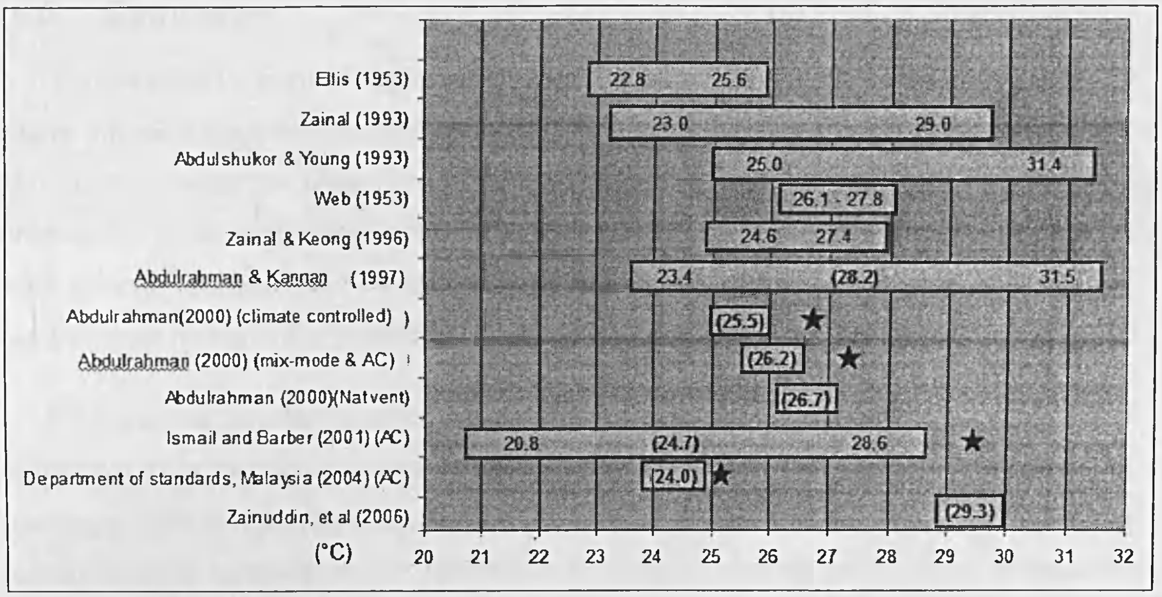
Zainal and Keong [22] conducted a field study of thermal comfort in two factories involving 119 female workers. The results were compared to ASHRAE standards 55–1981. A preliminary comfort zone model for Malaysia was proposed for Malaysian industrial workers, engaging in light, physical activity (1.7 – 2.0 met), in an environment with operative temperature of 24.6°C to 27.4°C, average air velocity 0.3 m/s and 18% to 75% relative humidity with a neutral temperature of 26.0°C.

Abdul Rahman and Kannan [23] conducted a survey to study and determine the comfort conditions of college students in their naturally ventilated classrooms. The result showed the comfort temperature to be 27.4°C. The range of comfort temperature was between 23.4°C to 31.5°C. The mean temperature found in the classrooms was 29.8°C and the mean air movement was 0.27m/s, with an average relative humidity of 65%.

Zain-Ahmed et al. [24] conducted a study on 21 year old students in an educational institution and showed a comfort temperature range of 24.5°C to 28.0°C with 73% RH. The optimum comfort temperature was 26.3°C.

Ismail and Barber [25] studied thermal comfort in Malaysian air-conditioned offices to check whether the current recommended indoor design condition corresponds with the comfort needs of Malaysians. The result produced a comfort range between 20.8°C to 28.6°C that was much wider than the comfort temperature range recommended by ASHRAE and the Malaysian Department of Standards [17] (23°C-26°C). Their recommended comfort temperature for Malaysian office workers is 24.7°C, which agrees generally with other field studies in air-conditioned environments in the tropics (which range from 24.2°C to 24.5°C) and was higher than studies in temperate climates [15, 26]. However, the average measured office temperature was 23.1°C, showing that Malaysian air-conditioning designers and operators do not adhere to the recommended indoor design temperatures.

Zainudin et. Al. [27] conducted a field survey on naturally ventilated classrooms in Kuala Lumpur. The neutral temperature proposed is 29.3°C., which is higher than the mean temperature experienced. The findings discussed in this section are summarised in Figure 4-3.



Note: ★ indicate values for air-conditioned occupancy, values in bold and brackets are neutral temperatures.

Figure 4-3 Comfort range and thermal neutralities established from various studies in Malaysia

4.4 Thermal comfort in residential buildings

All the studies discussed in the preceding sections deal with buildings of a non-residential type. The comfort condition examined in the current study is distinctive from the other studies presented here in two ways. The study focuses on night time occupancy, where the ambient condition is cooler by 8-9ºC compared to the daytime condition. On top of this, the predominant activity during the night is sleeping. Information on this aspect of thermal comfort in Malaysia is important, as there are a growing number of households utilising air-conditioning units. This study aims to fill this gap in information

Upon investigation of existing literature, no thermal comfort study (climate chamber or field survey) on residential buildings in Malaysia can be found. A simulation study of air-conditioned apartment buildings in Kuala Lumpur was conducted by Ahmad and Hyde [28]. Based on Auliciem's [29] equation, they proposed a neutral temperature for Klang valley (the area of the current study) of T_n = 26.1°C. For 90% acceptability, the comfort zone is proposed to be from 23.6°C to 28.6°C. However the thermal neutrality was developed for a naturally ventilated apartment. For air-conditioned apartments, they only proposed a range of acceptable thermostat settings using these values. As such thermal neutrality for air-conditioned occupancy, whether for daytime or night time occupancy cannot be established from their study.

4.5 Summary

The studies in tropical regions including those conducted in Malaysia reveal, a higher comfort temperature compared to those recommended by ISO and ASHRAE standards. These discrepancies in standards and actual thermal neutralities could potentially result in the waste of energy and unnecessary cooling. In some buildings with climate control, the average air temperatures were lower than the neutral temperature found in the respective samples studied.

The thermal comfort studies conducted in Malaysia so far do not cover thermal comfort during the night or thermal comfort in air-conditioned spaces in residential buildings. Thermal comfort research in air-conditioned rooms conducted in Malaysia has up to now, focused on non-residential buildings, focusing exclusively on daytime occupancy. No night time study can be found in the literature. Information on typical or average clothing values and metabolic rates for night time activities in homes are currently not available in the literature. Another aspects which differentiate the focus of the current study from the rest is in the difference in time of the day the units are used, hence the difference in external ambient conditions. All these issues warrant an exclusive research need in this area of study.

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5 Environmental performance of Malaysian housing and the use of air-conditioners

5.0 *Introduction*

The thermal comfort conditions and the need for air-conditioning in Malaysian homes are partly attributed to the internal conditions experienced by their occupants. This section presents the environmental design and performance of houses in Malaysia. Firstly the distribution of various housing types is investigated. Following this is a discussion of the thermal performance of these houses. Several studies of the thermal satisfaction of occupants are also discussed.

A discussion on domestic air-conditioners is conducted to provide a general picture on the use of this appliance in Malaysian homes. Several studies conducted in other countries are cited to provide background information on the important issues in the use of air-conditioning use in homes.

5.1 *Building Materials and constructions*

Generally, the materials used in Malaysia for residential purposes are brick, and timber, with a small percentage of natural materials such as bamboo, attap[8] etc. The table below gives the broad percentage of materials used as external walls for houses in Malaysia in 1991.

Table 5-1 Percentage of various materials used as external walls in houses

Materials	Urban (%)	Rural (%)
Brick, masonry	62	17.8
Timber	25.6	59.3
Hybrid timber/brick	11.9	20
Others	0.5	2.9

-Source- General Report of Malaysian People and Housing Census 1991. Department of Statistic, Malaysia

It can be seen that the number of houses with masonry construction form a cumulative percentage of 62% of urban households. With continuing urbanisation,

[8] Named after the attap palm, which provides the leaves with which the roofs are thatched.

the percentage of people living in modern mass housing will grow. This means that the percentage of houses with this type of construction will increase.

5.2 Comfort Requirement in Uniform Building By Laws (UBBL) 1984

There are a few legislative requirements which directly and indirectly affect the thermal comfort condition in Malaysian housing. In the Uniform Building By Laws 1984, Part 3, under Space, Light and Ventilation Headings, item no 39 reads:

"Every Room designed, adapted or used for residential, business or other purposes except hospitals and schools shall be provided with natural lighting and natural ventilation by means of one or more windows having a total area of not less than 10% of the clear floor area of such room and shall have openings capable of allowing a free uninterrupted passage of air not less than 10% of such floor area" [1]

It should be noted here that the By Laws does not dictate whether this passage of air should be dedicated (like a vent block) or adjustable (like a window). If air-conditioning is used, a dedicated opening would have caused inefficiency in the operation of the units due to high temperature and high humidity level of outside air. In terms of thermal comfort conditions, unlike non residential buildings, there is no performance specification for residential buildings.

5.3 Housing typology

Census data on housing, from the Department of Statistics, categorises houses into several types. Table 5-2 shows the distribution of house types in Malaysia. The data is from the National Survey report 1991 [2] and is segregated between urban and rural distribution.

Table 5-2: Distribution of various categories of housing

Type	No of households in Urban area	%	No of households in rural area	%	Total	%
Detached	606,900	29.5	1,391,900	69.5	1,998,800	49.2
Terraced	821,100	39.9	252,900	12.6	1,074,000	26.4
Semi Detached	235,600	11.4	188,700	9.4	424,300	10.4
Flat/Apartment	263,800	12.8	19,900	1	283,700	7.0
Shophouses	95,200	4.6	39,900	2	135,100	3.3
Longhouses	1,500	0.1	74,600	3.7	76,100	1.9

Misc	34,800	1.7	34,100	1.7	68,900	1.7
Total	2,058,900	100	2,002,000	100	4,060,900	100.0

Source- General Report of Malaysian People and Housing Census 1991. Department of Statistics, Malaysia

The total number of households in Malaysia in 1991 is 4.06 million. From the table it can be seen that in the urban area, the largest number of houses are in the form of terraced (or linked) houses (40%), followed by detached houses (29%) and Flat/Apartment (13%). In the rural area, the highest percentage is the detached house (69%), followed by terrace (13%) and semi-detached (9%). The following section looks into these house types in detail.

5.3.1 Detached house: Traditional

Traditionally people in the region had been living in detached houses. The generic term for the traditional house in Malaysia is Rumah Melayu (Malay House). Figure 5-1 shows a typical Malay House in the state of Malacca.

The constructions of these houses are characterised by lightweight timber constructions, raised on stilts. The stilt constructions are adopted to avoid seasonal flood or even surface water during heavy rains. The low thermal mass allows the internal condition of the house to follow closely the ambient condition. During the night this is favourable due to the cooler ambient temperature. High level openings allow freer air movement, which is the main strategy for cooling in this climate. However, no empirical study has been conclusively done on the actual thermal performance of these houses.

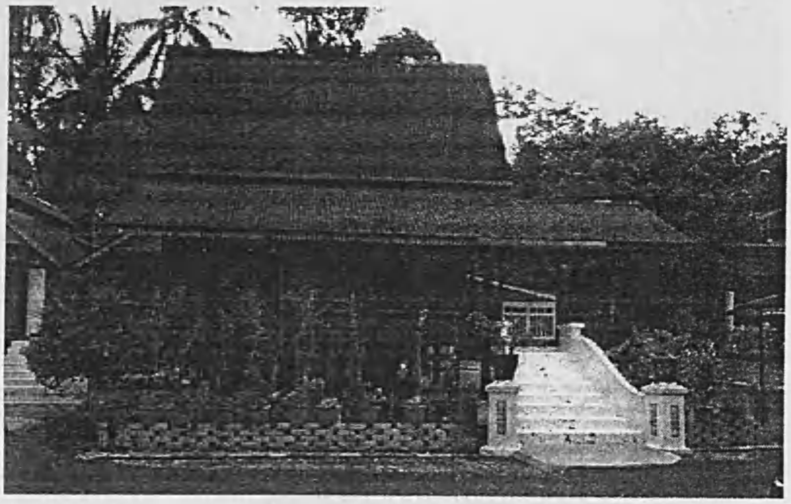

Figure 5-1: A traditional Malay house (source: Author 2004)

These houses can still be found throughout the country, especially in rural areas. The age of existing traditional houses range from 30 years to 100 years. The houses have undergone several modifications with the advent of modern technology and materials. The most frequent modification to these houses is the replacement of the traditional roofing material, *attap*, with metal roofing. The traditional *attap* is made of weaved palm leaves and has very low conductivity. As such this type of roofing performs well in blocking strong solar radiation. The recent use of metal roofing has resulted in severe discomfort during the day. To overcome this problem, a flat plaster ceiling is introduced into these houses. This has another unfortunate effect, that is, the closing of the roof space, which traditionally had been the escape route for hot air to accumulate and permeate to the outside through lavish openings in the gable.

Another modern modification to these houses is the introduction of additional spaces of masonry construction, normally attached to the back of the house. These spaces will normally be occupied during the day when the timber construction is too hot during the midday and afternoon period.

5.3.2 Detached houses - Modern

Modern detached houses or bungalows are mostly of masonry construction and range from $140m^2$ to $370m^2$. Figure 5-2 shows an example of a modern house.

Figure 5-2: Modern detached house (source: www.malton.com.my)

They can either be single or double storey. They typically fall within the high cost category. The walls are made of clay or cement bricks with plaster on both sides. Cement or clay tiles are used for roofing. Normally there is no insulation layer within the building envelopes. However, some developments do have rockwool and aluminium foil lining in the roof constructions of their houses.

5.3.3 Semi-detached houses

In this type of house, two adjacent properties are combined and share a party wall. Building regulations dictate that there should be a 20' (6m) setback from the front road, and 10' (3m) setback for the remaining sides. They can either be single or double storey. A typical footprint of built up area is 6m by 17m. The walls are made of clay or cement bricks with plaster on both sides. Cement or clay tiles are used for roofing. Typically they are of medium and high cost, ranging from $92m^2$ to $140\ m^2$ total floor area. (Figure 5-3)

Figure 5-3: Semi-detached houses (*source: www.bernardrealty.com.my*)

5.3.4 Terrace/ row/ link house

A maximum number of 16 units of houses with 6m frontage are linked together to form a row. There is a 6m vehicular road at the front and a smaller 3m service lane at the back. A typical lot size is 6m by 25m. They can be of low, medium or high cost, and either single or double storey.

The walls are made of clay or cement bricks with plaster on both sides. Cement or clay tiles are used for roofing. To overcome the problem of ventilation for the single storey type, some houses incorporate an air well in the middle of the house.

Figure 5-4 and Figure 5-5 shows an example of double storey and single storey terrace houses respectively. The houses are attached to each other on their longer sides, thus limiting the possibility for fenestration to the narrow front and back elevation.

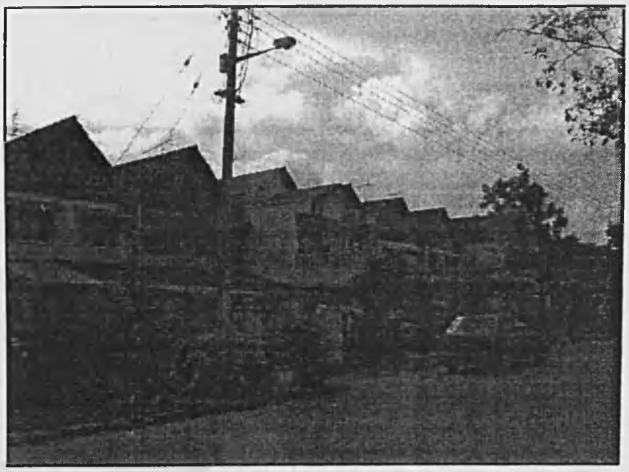

Figure 5-4: Double Storey terrace houses (source: Author 2003)

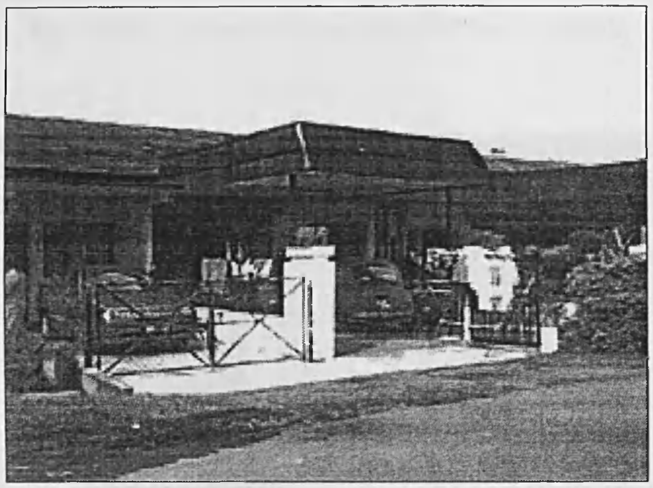

Figure 5-5: Single storey terrace houses (source: Author 2003)

5.3.5 Flat/apartment/condominium

This category of housing represents 13% of households in urban areas. In this type of housing, single level accommodation is grouped in a row or cluster and stacked on top of each other into a vertical block of up to 20 storeys. They can either be low (Figure 5-6), medium or high cost (Figure 5-7). Typical floor area ranges from $90m^2$ to $110m^2$.

The thermal performance of these houses is slightly better than other house types due to the fact that for intermediate units, thermal gain from roof is eliminated by having another flat on top. The thermal performance of the topmost units, on the other hand, is similar to terrace houses.

Figure 5-6 Low cost flats (source: Author 2003)

Figure 5-7: Medium cost apartment (source: Author 2003)

5.3.6 Shop houses

In this category, one to three storeys of apartment units are placed above shop or office units. A typical configuration is 6m frontage and 18-21m long. A central staircase connecting the units also performs as air and light well for the internal rooms. The walls are made of clay or cement bricks with plaster on both sides. Cement or clay tiles are used for roofing. The thermal performance of these houses is similar to the link house types.

5.4 *Environmental conditions of residential buildings*

The environmental conditions of residential buildings in Malaysia are discussed in this section. Several studies investigating the environmental performance of residential buildings are discussed below.

Sapian [3] collected interior climatic data of a typical unit from a low cost 18 storey block of residential flats in Kuala Lumpur. The climatic data collected ranges from 26.0°C – 29.5°C with 75%-90% RH and were superimposed on the bioclimatic charts developed by Szokolay [4]. The result showed that air movement of 0.5 m/s to 1.0 m/s is required to cool the occupant.

Hwa [5] conducted a series of surveys on thermal comfort satisfactions in single storey houses and low cost flats in Seri Kembangan, Serdang (25km south of Kuala Lumpur). Liang [6] conducted similar studies but focused on double-storey low cost houses instead. Both studies have similar findings. Around 75% of occupants complained that their house was too hot. Both studies also suggest that the thermal comfort problem in these houses is a result of building design and/or construction that is not responsive to the climate. In all cases, ceiling fans were employed as a cooling mechanism, frequently with more than one unit installed.

Jones et al [7] conducted a field survey of environmental conditions on several modern low cost houses in Penang, North Malaysia and compared the performance with a traditional house, constructed in timber. He found that the internal conditions of the modern low cost houses have lower temperature than the traditional house during the day. However, the situation is reversed during night time. This can be explained by the fact that the modern houses, being of heavy construction (masonry) absorb some heat during the day, and released it during the night. Since people spend more time during the night at home, he believes that the night time performance would be the key performance indicator in thermal performance assessment. Thus he suggested that the traditional house as the better alternative in terms of thermal comfort provision.

These studies describe the general environmental conditions and user satisfaction in Malaysian homes. They are not standard thermal comfort studies as commonly done in a normal thermal comfort field survey, where values for thermal neutrality would be established. At the moment of the writing of this thesis, no such study in Malaysia can be found in the literature.

5.5 *Air-conditioning use in homes*

This section investigates the use of air conditioners in Malaysian homes. A description of typical systems is presented first. Following this, the energy demand from their use is explored. Information from the available literature is limited to the number of households with air conditioners and the energy implication of their use. There is little information available on household characteristics, operational characteristics and system types. Several studies carried out in other countries are cited here for comparison and place the current study in a wider context.

5.5.1 System descriptions

5.5.1.1 Unit types

Residential air conditioning in Malaysia mostly employs the use of room air-conditioning units. Central air-conditioning is employed in institutional buildings. Currently there are three major types of air conditioning units used in the domestic sector.

a. Window Unit:

This is a self-contained packaged air-conditioner where all the components are housed within the unit. It is installed through an opening in the wall and no inter-piping connections are required.

b. Split Unit:

This unit comprises of two parts – the indoor Fan Coil Unit (FCU) (See Figure 5-8) and the Outdoor Condensing Unit (OCU) (See

Figure 5-9). The OCU consists of a compressor and a heat rejecting condenser coil while the FCU works as a cooling coil. Interconnecting piping between CDU and FCU is required to run this system.

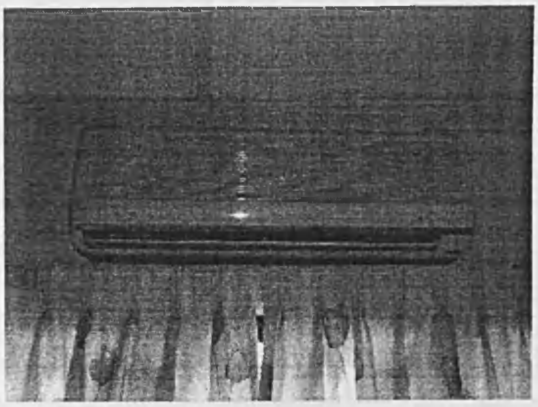

Figure 5-8 Indoor unit, containing fan coil and blower (source: Author 2003)

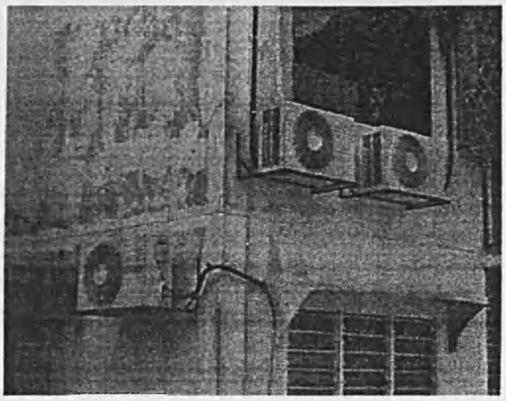

Figure 5-9 Outdoor units, housing the compressor and heat rejection fan ((source: Author 2003)

c. Centralised Multi System:

The centralised multi system requires only one outdoor unit. The outdoor unit will simultaneously cool multiple indoor units. Generally, the outdoor unit is either an inverter driven direct expansion system or chilled water system

Based on a few telephone conversations with manufacturers of air conditioners, almost all houses use single split units, the only option widely available from the market. According to Carrier Malaysia, one of the largest manufacturers, 95% of the units sold for residential use are single split units[9]. Central cooling or multi split units are used in a few exclusive bungalows and penthouses. National Panasonic said 99% of units sold for home use are of the single split type[10].

5.5.1.2 Control operation

The units are controlled by digital remote controls (Figure 5-10) or control pads attached to the indoor units. Users have the choice of setting the desired temperature (normally ranging from 16°C to 30°C). The temperature control is regulated by a sensor typically placed at the return air intake. However, the temperature setting does not accurately reflect actual condition maintained in the room, hence investigation of temperature setting on thermal comfort cannot be reliably deduced in this study.

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[9] Teleconversation with Christopher Haw, marketing representative of Carrier Malaysia Pte Ltd on 18 sep 2003

[10] Teleconversation with Andrew Chin, Technical Dept, National Panasonic Pte Ltd, Malaysia on 18 sep 2003

On top of this, users can choose between three to five levels of air speed of the supply air. The direction of cold air can also be set by adjustable fins at the supply outlet of the units. All units come with either digital timer or in some old models, mechanical timer for switching on and off operations.

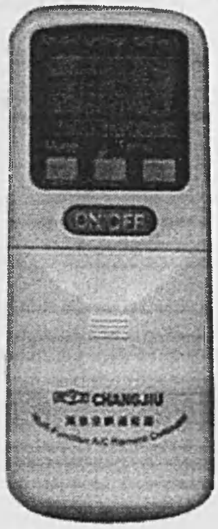

Figure 5-10 A typical remote control unit for split unit air conditioners (Source: www.germes-online.com/)

5.5.1.3 Power rating, cost and performance

The power rating of the units ranges from 1 hp (horse power) to 2.5 hp (746W-1865W). A 1hp unit would cost around MYR 1,000 (GBP 145) to MYR 2,000 (GBP 290). The price of the units are getting lower every year due to rising competition from rising number of manufacturers, stronger Ringgit value compared to the currencies of some producing countries and economies of scale as more household are using this appliance. These factors and the growth of income per capita experienced by Malaysia may contribute to the increasing the number of units being installed in Malaysian homes in the coming years.

The performance of a domestic air-conditioning system depends on several factors. Some of these are listed below:

1. Optimum match between power rating of unit and the cooling load of the air-conditioned space – a mismatch between power rating of the unit and the cooling load may result in inefficient energy use. Optimum efficiency is achieved at continuous running, it is important that the air conditioner be sized to achieve the longest run times possible. An air conditioner sized to

run continuously at design conditions requires less capital cost and will have a lower operating cost due to its longer run times.

2. Maintenance of system – In terms of periodic upkeep of the air filter and refrigerant level - It is necessary to keep the incoming air filter clean to reduce fan load in bringing warm air into the cooling unit. Reduction in refrigerant due to leak may results in ice formation in the cooling coil and restricts air flow, hence reducing the cooling capability of the unit.
3. Insulation of construction against external heat gain- Heat from the outside may enter into the conditioned room by conduction through the construction envelope. This results in higher cooling load and requires more energy for cooling.
4. Level of air infiltration between inside and outside: Malaysia experiences high humidity throughout the year. A high level of outside air infiltration may result in a lower sensible heat ratio, thus reducing the efficiency of an air-conditioning system. However, a minimum level of air-exchange between inside and outside is needed to maintain the healthy condition of occupants.
5. Type of control – The use of a thermostat may help regulate the temperature to the level desired by occupants. However, thermostatic switching on and off may result in more electrical energy being used during the on-off cycle of the units. An inverter control helps to regulate the cooling power by varying the power supplied to the compressor motor without the need to switch the motor on or off.

With the implementation of a minimum energy efficiency standard, it is targeted that all market air-conditioners should have a minimum Energy Efficiency Ratio (EER) rating of 10 [8]. EER is a measure of how efficiently a cooling system operates when the outdoor temperature is at a specific level (outdoor conditions commonly used is 35.0°C). The higher the EER number, the more energy efficient the system is. It is a measure of the ratio of the cooling power of unit over the power consumed by the unit.

5.5.2 Energy demand from the use of air conditioners in Malaysian homes

The use of air conditioners in Malaysian homes is rising rapidly. Table 5-3 below shows the number of air conditioners in the residential sector from 1970 to 2002:

Table 5-3 Number of Air conditioners in Malaysian homes 1970-1991

Year	Population	Household	Air conditioners units	Percentage (%)
1970	10 439 430	1 890 282	13,251	0.7
1980	13 745 241	2 503 974	57 340	2.3
1990	17 981 730	3 428 142	229 187	6.7
1991	18 379 655	3 537 606	253 399	7.1
2000	23 275 000	4 662 762	528 792	11.3
2002*	24 790 000	4 946 941	604 044	12.2

*Predicted

(Source: General report on population and housing census 1991. 1992, Department of Statistics, Malaysia: Kuala Lumpur, Masjuki et al., 2001)

The Economic Planning Unit of the Prime Minister's Department predicted the growth of the use of air conditioning units in homes until the year 2020. The data is shown in Table 5-4 below. It is estimated that the use of Air conditioners in homes consumes approximately 18% to 20% of total national energy use [9]. Using this information, Mahlia [10] predicted the energy used by the residential sector. Table 5-4 shows the predicted number of units and corresponding energy use from 2002 to 2020.

Table 5-4 Predicted number of air conditioning units in residential sector up to 2020 and the energy demand (Source: Mahlia 2002)

Year	Households	Air-conditioning units (AC)	Percentage of number of AC to number of Households	Annual Residential energy demand (GWh)	Annual national energy demand (GWh)
2002	4,946,941	604,044	12.2%	11,986	66,159
2003	5,093,688	643,586	12.6%	12,927	71,368
2004	5,243,539	684,406	13.1%	13,905	76,779
2005	5,396,495	726,504	13.5%	14,919	82,390
2006	5,552,555	769,879	13.9%	15,969	88,203
2007	5,711,720	814,532	14.3%	17,055	94,217
2008	5,873,989	860,462	14.6%	18,178	100,433
2009	6,039,363	907,670	15.0%	19,337	106,850
2010	6,207,842	956,155	15.4%	20,532	113,468
2011	6,379,425	1,005,918	15.8%	21,764	120,287
2012	6,554,113	1,056,959	16.1%	23,031	127,308
2020	8,063,382	1,511,276	18.7%	34,480	190,721

It can be seen from the two tables above that the number of air-conditioners in Malaysian households is growing rapidly. In 1970, the percentage of the number of air-conditioners to the number of households is only 0.7%. The percentage rises tenfold within 21 years to 7.1% in 1991. By 2020, it is predicted that this number rises to 18.7%, a 9.4% increase per decade. In examining the prediction proposed in these publications, it is found that the potential impact of global warming on the use of air-conditioners is not taken into account. It can be hypothesized that rising global temperatures will push this number even higher. It is clear that the impact on energy demand from the use of this appliance will increase in significance in the future.

5.6 Domestic air- conditioners use pattern

The energy demand resulting from the use of air conditioners is determined not only by the difference between ambient temperature and desired temperature, but also by the operational issues and user behavioural pattern. In the domestic situation, where occupants have the choice as to when to use air-conditioning and at what temperature setting, behavioural issues play an important role in determining the total energy demand. No information on the pattern of air-conditioning use in Malaysian homes can be found in the literature. As such, the findings from studies elsewhere are also discussed here.

5.6.1 Operational issues

Jian and Jiang [11] conducted a field study on 42 residences in Beijing using air conditioners. None of the cases used central air conditioning. It is found that the units are used intermittently, mostly throughout the evening and night time. About sixty percent of the rooms monitored were bedrooms while the rest were living rooms. It was found that the use of air conditioners is more frequent and more extensive in the bedrooms than in the living room. They concluded from the study that occupants would switch on the air conditioners when the air temperature reaches 39°C. They will only turn off the units if the temperature drops below 26°C. A reduction of 1°C in the desired room air temperature will result in an increase in cooling load of 7-8%. They carried out a simulation study based on the patterns of use found in their survey. They found that the intermittent use pattern as found in their study has the potential of saving 33% of energy use as opposed to the continuous pattern found therein.

Kempton et.al [12] conducted a study of the operation of room air conditioners in 62 apartments in New Jersey, in the United States of America. He monitored the use of air conditioners over 115 days in each apartment. It was found that across physically similar apartments, seasonal air-conditioning energy consumption varied by two to three orders of magnitude while interior temperature varied by only 2.4°C to

3.7°C. Comparing use patterns and information from user interviews between two extreme cases, it is found that the lowest consumption (corresponding to higher average internal temperature) was due to infrequent use of air conditioning as the user does not actually feel the need to use the units. On the other hand the high consuming apartment (with lower internal average internal temperature) left their units running all the time.

He also compared the energy use between units being left to run continuously (in one apartment) all day and controlled by proper thermostat setting and those being switched on and off manually for short periods as needed by occupants. He found that the case with continuous operation uses seven times more energy than the average consumed by those manually switching their units on and off, even though the later typically set their thermostat at highest (coldest) setting. This may largely be due to the much shorter period of use (between 3 to 5 hours a day) by those relying on manual operation.

Ahmad and Szokolay [13] conducted a simulation study on energy use in Malaysian residential building. Although the study focuses on multi-storey urban residential buildings, its recommendation for optimum operation of air conditioners is worth mentioning here. Working with Auliciem's equation for comfort based on Malaysian weather data, they established general comfort range for comfort in Klang Valley (the study area) as between 23.6°C and 28.6°C for 90% occupants' acceptability. They use these values as the thermostat settings for the simulation of air-conditioned rooms in their study.

No empirical study of air-conditioner use pattern has been found in Malaysia. This information is needed in this study to evaluate the performance of air-conditioners and the adaptive measures taken by occupants to achieve comfort in air-conditioned rooms. The preliminary study discussed in chapter 7 seeks to establish this information.

5.6.2 Use of comforters in air-conditioned bedrooms

Prior to the advent of air-conditioners, people go to sleep with either normal (single ply blanket) as covering or no blanket at all. With the introduction of air-conditioners, the use of duvet type blankets or comforters becomes a common practice in a warm climate such as Malaysia. Now every departmental store and every major retail outlet in Malaysia has a section selling this type of blanket in its home furnishing department (Figure 5-11).

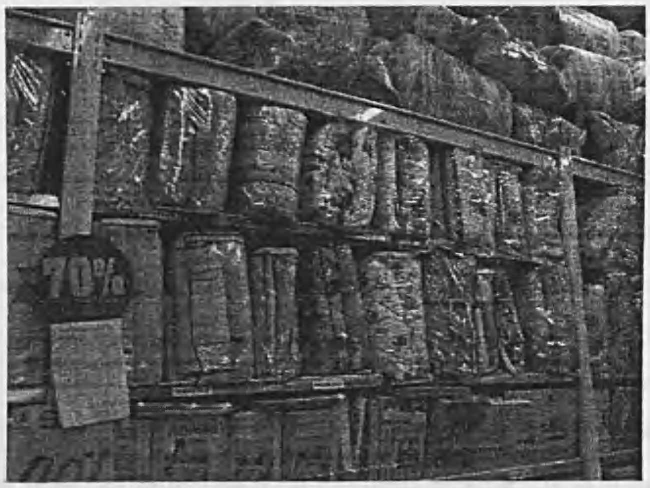

Figure 5-11 Comforters are now a common item in every major retail outlets in Malaysia (Source: Author 2007)

In Malaysia, the word comforter denotes a blanket type consisting of two layers of sheet, filled in between with natural or synthetic insulative material such as polyester wool. A twin size comforter weights between 0.7 to 1.0 kg. The insulating property can be anywhere between 3 to 5 clo. Unlike tog rating available for duvets in the UK, there is no standard rating for the insulating property of comforters in Malaysia.

Without air-conditioning, it is unbearable to sleep under such a blanket. This indicates a waste of energy as the primary use of a comforter is to keep a person warm, while energy is used by air-conditioning to keep condition cool. The reason for the use of this type of blanket has not been researched. At this juncture, it can be prematurely suggested that comforters are necessary in air-conditioned bedroom due to overcooling.

Psychological and social reasons for adopting this type of covering, however, should not be dismissed. Just as the noise of a fan can psychologically helps deliver the notion of comfort for people, the use of a comforter might add to the feeling of cool comfort in a warm climate. On top of this, browsing through various home design publications in Malaysia nowadays, the sight of a comforter spread on a bed is becoming a common feature and suggests ‘good taste’ in home decoration.

The current study nevertheless, investigates the implication of the adoption of this blanket type on the thermal experience of people as well as on the cooling energy requirement. The loss, or savings, from using different types of blanket, translated into financial figures or carbon emission values could hopefully motivate people to adopt good practice in the use of air-conditioners at home.

5.7 Summary

The environmental design of Malaysian housing is investigated. Although traditionally the houses are lightweight timber construction, the majority of new houses in Malaysia are constructed with high thermal mass, employing the use of masonry construction. The need for urbanisation means these houses are constructed densely, limiting the benefit of wind movement, a crucial factor in achieving comfort in such a climate. Several comfort studies conducted have shown that the use of ceiling fan is a must in order to achieve comfort in these houses. The high thermal mass construction provides reduction of daytime peak temperature but higher than external night time temperature. Since most occupants will be at home during night times, it is perhaps more important to give attention to the environmental performance of the houses during this time. Several studies conducted on the environmental conditions and users' satisfaction in Malaysian houses show the need for the improvement of thermal comfort conditions in these houses.

A growing number of households resolve these problems by installing air-conditioners. There is evidence that air-conditioning use in homes in Malaysia is rising rapidly. The energy demand will therefore become more and more significant with each passing year. Proper understanding of how people use their air-conditioners is necessary to predict and evaluate the energy impact and identify problems in the use of this appliance in Malaysia. There is a lack of information on the use patterns of air-conditioners in the residential sector. Research on operational characteristics, user behaviour and other issues exclusively for domestic setting is necessary in order to understand the long-term energy implication of air-conditioning use in homes.

The use of comforters in air-conditioned bedrooms indicates overcooling, since the use of this type of blanket is not common and made the user uncomfortably warm in non air-conditioned bedrooms in the Malaysian climate. An outcome expected from the current study is the evaluation of the effect of using this type of blanket on household energy consumption. This finding from the study hopefully will be useful to encourage people to adopt a more energy saving behaviour in using air-conditioners at home.

5.8 References

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PART II: METHODOLOGY

6 Research Methodology

6.0 Introduction

The main objective of the current work, as explained in Chapter 1, is to investigate the use of air-conditioners in Malaysian homes, in terms of operational patterns, thermal comfort conditions and the adaptive behaviour of occupants in air-conditioned rooms. The investigation thus focuses on the following questions:

1. What are the typical environmental conditions found in air-conditioned bedrooms during night time occupancy?
2. What are the characteristics of the units and how do occupants operate their units?
3. What is their adaptive behaviour in achieving thermal comfort during night time occupancy?
4. What is the range of thermal conditions within which occupants feel comfortable in air-conditioned bedrooms during night time occupancy?

These questions form the basis of the whole study. This chapter explains the methodology adopted for the study. The overall framework is explained first. Following this, the details of each phase of the study are elaborated.

6.1 Research framework

Figure 6-1 shows the framework of the study. First, a literature review was carried out to establish information on the development of thermal comfort study in general, other thermal comfort studies in hot humid regions, air-conditioning use in homes as well as the current environmental design and performance of Malaysian housing.

Following this, a preliminary study was carried out prior to a main survey. This consists of a general survey of 112 households and monitoring of internal conditions of 7 air conditioned bedrooms over a few days. The general survey was conducted with the help of enumerators visiting houses without any measurements taken. The data gathered in this survey provides crucial information not available in the literature, e.g. household profiles, air-conditioning unit types, typical location of installation etc. The subsequent monitoring campaign was conducted in seven households, selected from the surveyed samples to characterise the thermal profile of air-conditioned spaces over a few days. With the results and findings from the household survey and the preliminary monitoring, a clearer picture of air-conditioning use in homes is established. The area of investigation is subsequently identified, i.e. bedrooms at night time occupancy.

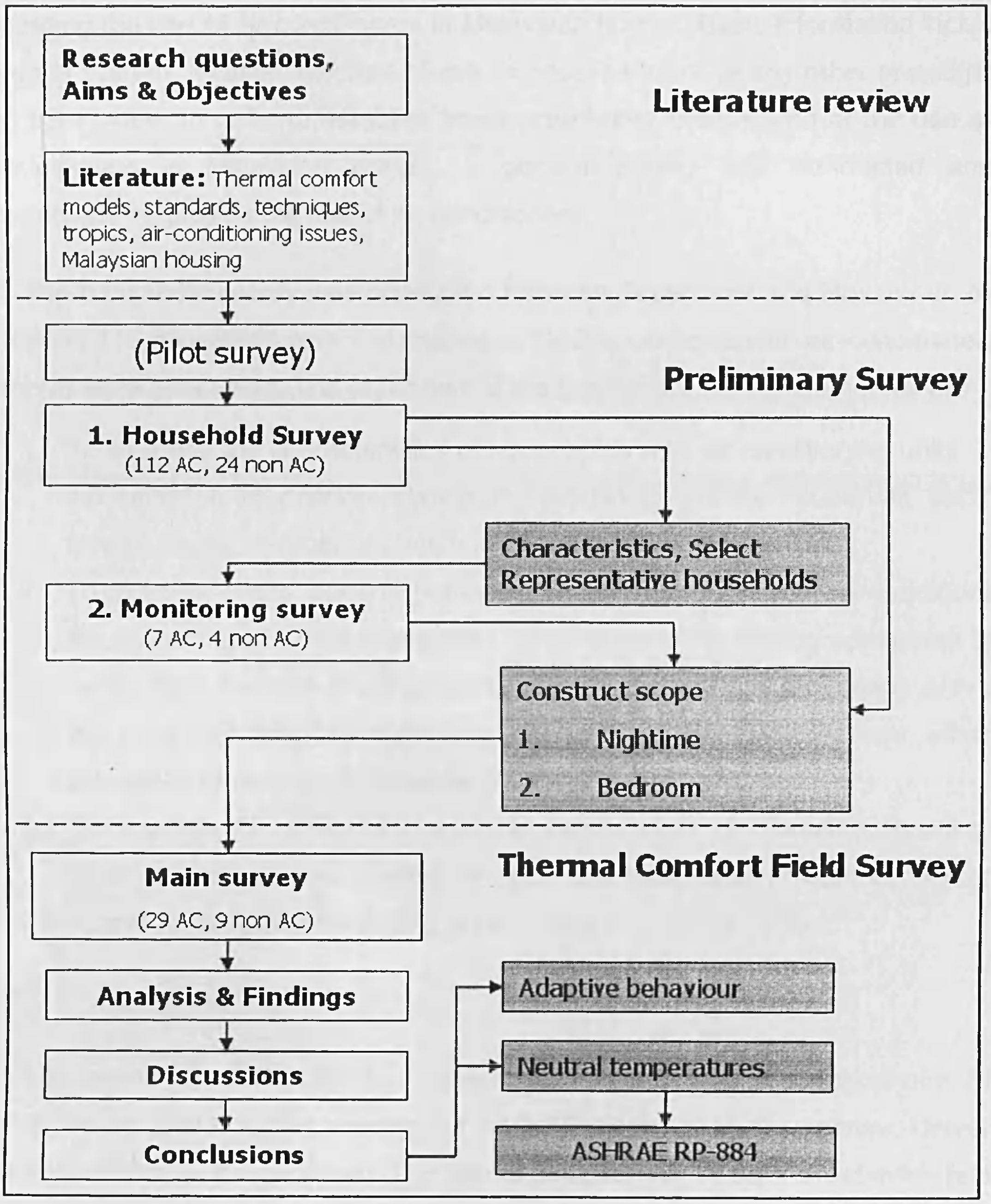


Figure 6-1 Research Framework

The main investigation, a thermal comfort field survey, was conducted by adopting a level 3 investigation according to Nicol's taxonomy [3], where data of all the six factors of thermal comfort, together with the subjective responses, were gathered from a total of 38 households. Information on adaptive behaviour is also gathered in self-completed questionnaires. The data acquired is used to establish thermal neutralities and acceptability for the study population. The datasets has been proposed to be included in the ASHRAE-RP884 project database [4] (see Chapter 3).

6.2 Preliminary Survey 1- Households survey

As had been discussed in chapter 4 and 5 that, apart from the number of units and energy demand, no other information can be found in the selected literature regarding the use of air conditioners in Malaysian homes. Basic information including types of system, location and time of use, is necessary before any other investigation can take place. In order to establish these preliminary descriptions of the use of air conditionings in Malaysian homes, a general survey was conducted among households employing the use of air-conditioners.

The household survey was conducted between September and November 2003. A total of 119 household personal interviews (112 households with air-conditioners, 7 without) were conducted. The objectives of the preliminary household survey are:

1. To examine the characteristics of households with air conditioning units. This will establish information relating to the building and the household, such as type of house, number of people in the household, etc.
2. To examine users' general behaviour regarding their use of air-conditioning. Issues such as thermal experience, use of alternative cooling appliances (e.g. ceiling fan), the use of coves during sleeping, etc. This information provides the range of adaptive measures adopted by occupants in their effort to achieve comfort in air-conditioned spaces.
3. To examine the characteristics of air-conditioning units installed, focusing on such aspects as the location of unit, unit type, type of control, period of operation, temperature setting, extent of use and power of unit.

6.2.1 Survey method

The survey was conducted by interviewers using a structured questionnaire. Prior to the survey, a pilot survey among staff of the Department of Architecture, Universiti Putra, Malaysia, was conducted. The aim of this pilot survey was to establish lists of issues about which questions might be of significance for the study. Among the issues established in the pilot survey was the predominant use of air-conditioning units during sleeping hours. Following this, two types of questionnaire were developed:

i. A questionnaire for the main group (households with air-conditioning units installed). (Survey form attached in Appendix 1)
ii. A questionnaire for the Control Group (households without air-conditioning unit). (Survey Form attached in Appendix 2)

The control group would provide comparative information with regard to the use of alternative cooling appliances (i.e. electric fans) and on the level of insulation in general.

The interviews were conducted by visiting houses in the selected areas. The respondents were exclusively the head of household or the person in charge of the finances of the household. The interviews were conducted during weekends when it was anticipated that most of the heads of household would be at home. Over the course of 4 weeks, a total of 119 households participated in the survey. 112 were households using air-conditioning, and 7 households formed the control group.

6.2.2 Questionnaire development

1. Questionnaire for main group

The questionnaire for the preliminary study is attached in Appendix 1. At this point in the study, it was not clear as to what were the important factors in characterising the use of air-conditioners in Malaysian homes. The questionnaire is divided into five main sections, as described below:

a. Description of property: the type of house, property price category, the orientation of main façade, general shading level, tenure, price of property and years of residence.
b. Description of household: the total household income, numbers of occupants and average electricity bills were inquired.
c. Description or air-conditioning system: the number of air-conditioning units, locations of each unit, frequency of use, units size and time of normal operation.
d. General use pattern of air-conditioners: The general maintenance interval, passive cooling measures adopted, factors considered in the decision to use air-conditioners.
e. Personal comfort level in bedroom and methods of achieving comfort: In this section, for each household, two respondents who are occupants of air-conditioned space give their responses. Questions regarding their adaptive behaviour in the air-conditioned room, such as general thermal sensations, clothing levels, use of auxiliary fans and other actions to achieve comfort were asked. The general thermal sensation was assessed using the ASHRAE 7 point thermal sensation scale [5].

2. Questionnaire for control group

The questionnaire for the control group (households without air-conditioners) is similar to the above, minus the section dealing with the general use pattern of air-conditioners.

6.2.3 Location of study

Areas chosen for this study are Section 18 and Section 20 in Shah Alam City Council area, approximately 25 km to the west of Kuala Lumpur. Figure 6-2 shows the maps of both housing estates in their entirety. Both developments were completed around the same time in 1995. They are housing developments representing typical modern housing developments in Malaysia. As such they are a mix of various house types and price categories.

6.3 Preliminary Survey 2 - Monitoring Study

Upon analysis of data from the household survey, it was found that the majority of houses have only one air-conditioning unit and that they are installed in the bedrooms. Following this, the next course of inquiry was to investigate the environmental conditions of the bedrooms where air-conditioners are installed. In the household surveys, respondents were asked if they would agree to participate in a monitoring study which will take course over a few days. From the samples, only 7 households with air conditioned rooms agreed to take part in the monitoring study.

The objectives of the monitoring study are:

1. To investigate the environmental conditions of air-conditioned rooms over a few days, comprising weekdays and weekend periods.
2. To establish the operational pattern of the air conditioning units.

For comparative purposes, the internal conditions of four non air-conditioned bedrooms were monitored first. In all cases, simultaneous monitoring of outdoor conditions was also carried out. The data was then fed into Excel and the profiles of air temperature and humidity plotted on a psychrometric chart for each case, and analysed.

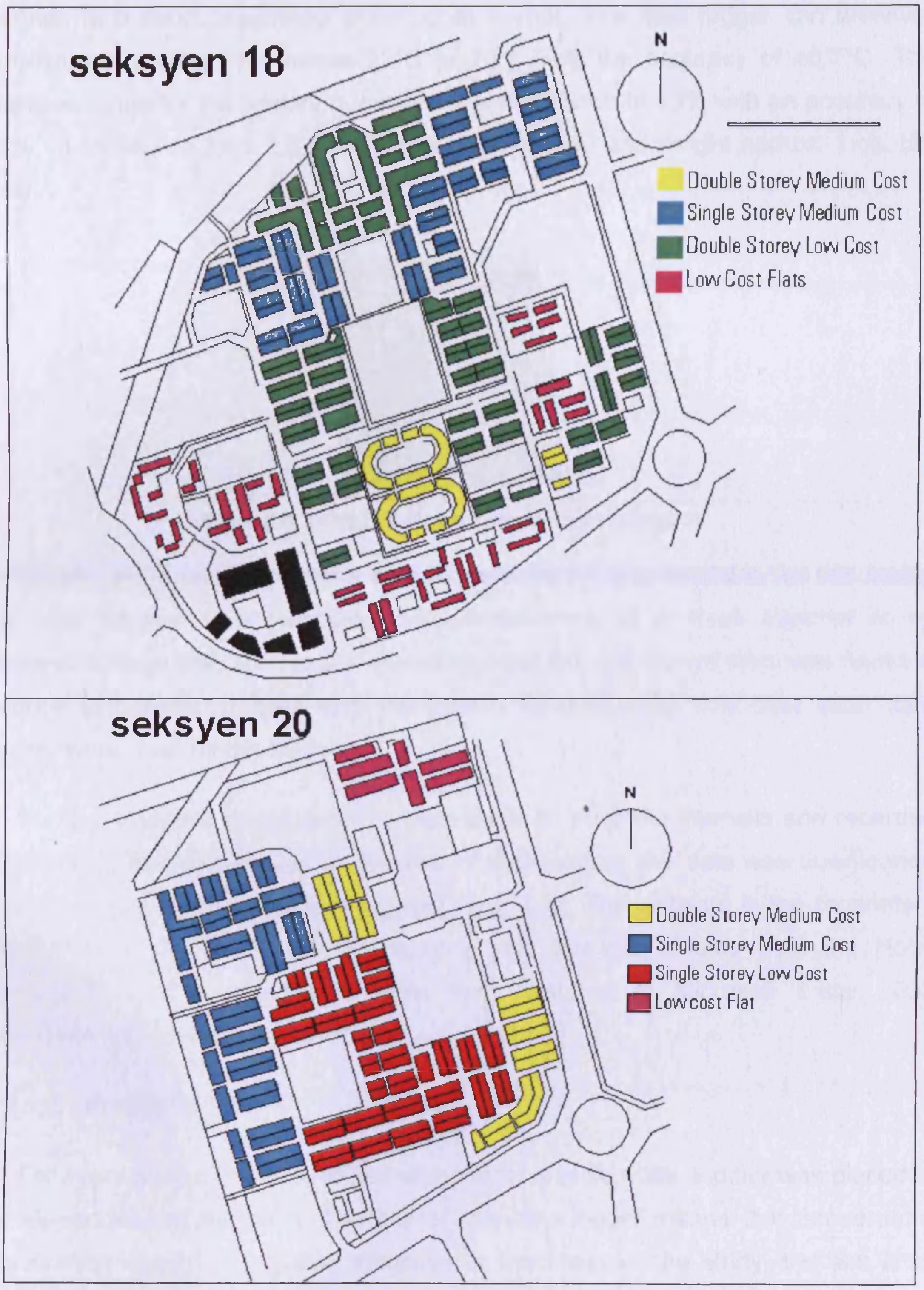


Figure 6-2 Map of Seksyen 18 and Seksyen 20 housing development, Shah Alam

6.3.1 Measurement of environmental data

The environmental data was measured using Onset HOBO RH/Temp data logger (http://www.onsetcomp.com) (see Figure 6-3). It is a 4-channel temperature and relative humidity data logger. It has the capability to measure and record up to 7,943 readings. The reading rate is user selectable with sampling intervals being 0.5

seconds to 9 hours, recording times up to 1 year. The data logger can measure temperature ranging from minus 20°C to 70°C with the accuracy of ±0.7°C. The operative range for the relative humidity sensor is from 0 to 95% with an accuracy of ± 5%. It measures 2.4 x 1.9 x 0.8" (68 x 48 x 19 mm) and weight approx. 1 oz. (29 gms)

Figure 6-3 ONSET Hobo Temp/RH data logger

Initially, ten numbers of these data loggers were made available for this study. The data loggers were calibrated by commissioning all of them together in an insulated storage box. The results were compared and only one of them was found to produce inconsistent results with the others. Subsequently only nine such data loggers were used for the study.

For the study the measurements were taken at 5 minute intervals and recorded continuously for several days. At the end of each survey, the data was downloaded by BoxcarPro software (http://www.onsetcomp.com). The software is the proprietary program that will handle the downloading and analysis of data from the Hobo dataloggers. The output files were then exported to Microsoft Excel 2002 spreadsheet for analysis.

6.3.2 Procedure

For every house, one data logger was placed outside while another was placed in the air-conditioned bedroom. The use of one data logger means that temperature stratification is not investigated. However at this stage of the study, the aim is to characterise the thermal variation of the air conditioned room rather than its relationship with thermal experience of a subject. As such the need for temperature stratification is not necessary. The data logger in the bedroom was placed at 1.5m above floor level. The parameters were measured at 5 minute intervals for several days. The actual number of days varies between cases, depending on the agreement with participants at the beginning of the monitoring. The parameters measured were air temperature and humidity level. The monitoring period ran from Mid December 2002 to February 2003.

6.3.3 Monitoring of non air conditioned houses

Monitoring of non air-conditioned houses was conducted first to establish the background information on the environmental conditions of Malaysian homes. The houses chosen for this study were located in the state of Selangor within 20km of Kuala Lumpur, the main capital (3°08'N, 101°44'E). Two of the houses were situated next to each other and monitored concurrently (Case no. C03 & C04). The distinguishing characteristic is the construction material. C03 is of masonry construction and C04 is of timber construction.

The data is then fed into Excel and drawn into time series profile charts and psychometric charts. The results are compared with the comfort zone as suggested by ASHRAE Standards 55 [5] and the comfort zone for Malaysia developed by Abdulshukor & Young [6]. The possible comfort zone developed by Szokolay [7] by means of higher air velocity is also included for comparison.

6.3.4 Monitoring of air-conditioned rooms

In the monitoring study of air-conditioned houses, all the rooms monitored were bedrooms except in one case, where the air conditioned space was the living/dining room. For medical reasons, this room was being used as a sleeping room. The significant difference was that this room was twice as large as the other bedrooms monitored.

At the beginning of the monitoring, a checklist of room size, opening sizes, construction and location was filled (Appendix 3). A sketch plan is drawn to indicate the location of the unit, the bed and door and windows. The occupants of the monitored room were given a log sheet (Appendix 4) which they had to fill in to record room occupancy, times when the unit was switched on or off, temperature settings and the unit's fan setting. With the results and findings from the household survey and the preliminary monitoring, a clearer picture of air-conditioning use in homes is established. An area of investigation is thus identified. It is decided that the area of investigation for the thermal comfort field survey is the use of air-conditioners in bedrooms during night time occupancy.

6.4 *Thermal Comfort Field Survey*

From the analysis of the preliminary studies, it is established that in all cases, the first place in a household where air-conditioners are installed are the bedrooms, and they are being used predominantly during sleeping hours (the results of the preliminary studies are discussed in the next chapter). Following this, a level 3 investigation according to Nicol's taxonomy [3] (See section 3.4.1) was carried out in 29 households. Another 9 households without air-conditioning were also monitored to provide comparative information.

6.4.1 Survey area

The houses chosen for this study are located in the Klang Valley, an area covering 25 km radius, with Kuala Lumpur being in the centre (Figure 6-4). All the houses have their air conditioning unit installed in the bedrooms and are used during the night.

Figure 6-4 Map showing Klang Valley area (within 25km radius of Kuala Lumpur)

This area includes the preliminary surveys conducted previously. However, the larger region is chosen to obtain adequate number of willing households for the detail monitoring study.

6.4.2 Sample Selection.

A total of 200 invitation letters were sent around the survey area, although a total of 50 houses were targeted. Only invitations to subjects who have been personally introduced by mutual contacts were willing to participate. Eventually, only 36 households were able to be monitored within the time available. The condition for participation was that the household must have an air-conditioning unit installed in an occupied bedroom. Upon completion, it was found that data from 7 households were not usable for analysis due to various reasons, such as power disruption, disturbed sensors which cause missing sets of variables, etc. Another set of invitation was sent to households without air conditioning for control purpose, to which a total of 9 households responded.

In this study, both transverse sampling and longitudinal sampling is possible. Transverse sampling analysis may be done by binning results into individual households, and also by differentiating votes by individual subjects.

Longitudinal sampling is done by asking subjects to cast votes at various times of the night, namely, at the time of going to bed, at any time when the subject wakes up during sleeping hours, and at the time when the subject wakes up for the day. As such, each subject casts a minimum of two votes. If the subjects happen to wake up during the night, the number of votes can be three or more, depending on the number of times their sleep were interrupted.

6.4.3 Period of survey:

Upon detailed analysis of the use period from the 24 hour chart disc in the preliminary survey form (see appendix 1), it is found that the units are most likely to be used from sunset to early morning. The monitoring for the field survey therefore ran from 1800 to 0800 the next day.

6.4.4 Time of survey

During the course of the study, monitoring was conducted between November 2004 and May 2005. This study is thus restricted to this period of the year. However, the seasonal variation of monthly mean temperatures for the Malaysian climate does not vary greatly with the yearly annual range as low as 2°C. Hence, there is no clear distinction between winter and summer as in a temperate climate. It can thus be proposed that the findings can be generalised for the whole year.

6.4.5 Instrumentation

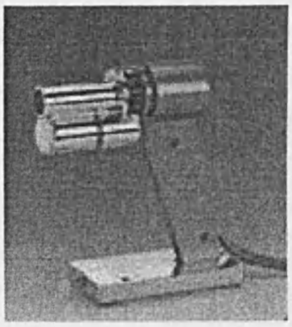
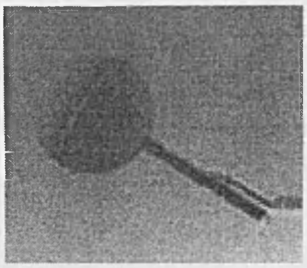
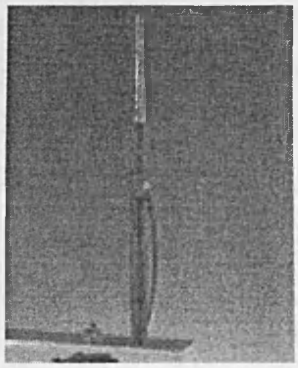
This section describes the instruments used in measuring the internal and external environmental conditions and the survey forms in the preliminary survey.

6.4.5.1 Measurements of internal conditions:

Environmental conditions were monitored using the Babuc thermal comfort meter system, manufactured in Italy (http://www.lsi-lastem.it/). It consists of an 11 channel data logger with probes (see Figure 6-5). The model and specification of the thermal comfort meter system is shown in Table 6-1.

Figure 6-5 Babuc Comfort meter set in bedroom

Table 6-1: Model and specification of Babuc Thermal Comfort Meter System (Source: Lastem publication no MW8505-09/04)

Item	Description	
1	Data Logger: Model no: BabucA (BSA010). Multiple-data logger with 11 inputs, 20,000 sample memory capacity (64Kb).	
2	BSU102 Psychrometer: This probe is a psychrometer for measuring air temperature and humidity and the other connected quantities (dew point temperature, absolute/relative humidity). In the pipe where the two sensors are lodged, protected from solar light, the air is forced from a fan at a speed of around 4 m/s. This probe is made up according to the ISO 7726. Accuracy ±0.133°C,±0.1%RH	
3	BST131 - Radiant Temperature The probe is realized according to the ISO 7726. This sensor is compatible with cordless system (cod. DME810, DME811). Accuracy +0.19°C.	
4	The BSV101 hot-wire anemometer measures air speed. This probe is manufactured in accordance with ISO 7726 standards. The probe allows air speed to be measured in all directions. Accuracy +5cm at 0-0.5m/s, +10cm at 0.5-1.5m/s.	

All the sensors are in compliance with ISO 7726 Ergonomics of the thermal environment - Instruments for measuring physical quantities [8]. The environmental parameters directly monitored are:

1. Dry bulb Temperature
2. Wet bulb (forced ventilation) temperature
3. Globe Temperature
4. Air speed

These variables are then downloaded to a computer using Infogap Software (http://www.lsi-lastem.it/). The Infogap software then calculates these variables to produce derivative variables, i.e. mean radiant temperature, operative temperature and relative humidity. Table 6-2 below shows the summary of the environmental variables acquired during the monitoring survey.

Table 6-2 Variables of a environmental data acquired for the current study

Variables directly measured	Derivative variables
1. Dry bulb temperature 2. Wet bulb Temperature 3. Globe Temperature 4. Air speed	1. Mean radiant temperature 2. Operative Temperature 3. Relative Humidity

6.4.5.2 Measurements of external conditions:

A 4-channel HOBO data logger (see 6.3.1) was used to monitor the external air temperature and humidity. The data logger was set to acquire data at 5 minute intervals.

6.4.6 Development and structure of Questionnaire and survey forms

This section discusses the development and the structuring of the questionnaire survey forms used in the main field survey. A few survey forms are used during the monitoring. Apart from item 1, the survey forms are attached in Appendix 5. The development and structure of the questionnaire is discussed below.

i. Room checklist: This is a record of information of the characteristics of the room monitored. This is similar to the forms used in the preliminary monitoring and attached in Appendix 3.

ii. Household general description: (Form no. 1)
Information such as date of monitoring, address, house type and the number of household occupants are recorded.

iii. Respondents' personal information: (Form no 2)

To be filled by each occupant of the monitored room. Two sets of such questionnaire are given to each household, with identification of subject number (in cases where there are two occupants). The items asked in this form are discussed below

a. Thermal sensation votes

The various scales of assessments used by researchers carrying out research in thermal comfort have been discussed in section 2.1.4. In the study, only thermal sensation scale is used. Thermal preference scale, normally used in more recent field surveys, is not used. The current study contends that, in a scenario where occupants have a high number of options to control the environmental conditions (by operation of air-conditioning units and auxiliary fans), it is sufficient to obtain the thermal sensation alone, as inherent in ASHRAE scale, because the notion of occupants preference is taken care of by the personal choice of air-conditioners control setting. Therefore, ASHRAE 7 point thermal sensation scale is used in this section. All the respondents in the survey understand English and need no translation of the survey forms. In a few cases, due to the need to maintain the sensitivity of the scale, a brief explanation is given on the use of the sensation scale in Malay. The translation is standardised as these: Hot = 'sangat panas', warm= 'panas', slightly warm = sedikit panas, ok=ok, slightly cold= 'sedikit sejuk', cool = sejuk, cold = 'sangat sejuk'. Votes were to be cast at the time of going to sleep, mid-sleep (if subject wakes up during normal sleeping hour) and waking up for the day. The time when each vote is cast is also recorded.

b. Humidity sensation votes

Humidity sensations are cast on 5 point symmetrical Likert scale (Humid = -2, slightly humid=-1, OK=0, slightly dry = 1, Very dry=2). The votes were to be cast at the same time as the casting of the thermal sensation votes.

Respondents were not asked to wake up purposely during the night to cast vote. However, they were asked to cast vote whenever they woke up during the night to adjust the air-conditioners. This would help in the understanding of sleep disturbance in order to carry out adjustments to the operation of air conditioners. The number of times and the time a subject wakes up in the middle of sleep can be obtained from the number of votes cast in between 'going to bed' and 'waking up'

c. Blanket thickness and use

Blanket thicknesses are categorized into two types, namely normal blanket (single ply sheet) and comforters (see section 5.6.2). The extent of covering of the body is also recorded; not used, half body and full body. The use is recorded during three phases of sleep; early sleep, mid sleep and at the time of waking up.

d. Clothing articles

Respondents are asked to identify the articles of clothing they use during sleeping. A list of common articles of clothing found in the preliminary survey is presented in a table.

iv. Operation of Air Conditioning unit (Form no 3)

Respondents are asked to record the start – stop time, use of timer, temperature setting, and fan blower level. For each action, the time it is executed is noted. Adjustments to control settings, if any, are recorded in another similar table.

v. Operation of electric fan (Form no. 4)

The use of electric fan, either ceiling, table or standing fan is recorded. Respondents are asked to indicate the time of operation and the fan speed level (Between 1 and 5)

6.4.7 Procedure

The study begins in the afternoon, typically between half to an hour before 1800. Occupants were briefed of the procedure involved and given instructions on how to fill in the survey forms and questionnaire.

The meter is set at 0.6m above the floor and closest to the sleeping positions of one of the occupants. The decision to place the instrument is made carefully so that there is no rearrangement of the main furnishing, in order to preserve the normal arrangement they use everyday. In such a situation, it is difficult to standardise the position of the comfort meter in each case, as the bed arrangement, and its relation with the air-conditioning unit and other furniture and walls differ between cases. However, care has been taken to avoid placing the meter directly in the flow of the air-conditioning unit supply air stream. This is to ensure the temperature measured is that of the ambient condition of the room.

The comfort meter was set to start monitoring at 1800 and to stop at 0800 the following day. Environmental data were logged at 150 seconds interval. This interval was chosen due to the limitation of the file size of the data logger. The chosen interval allows maximum continuous monitoring for 14 hours, the duration needed for the study. A Hobo data logger was used to measure simultaneous external conditions at the same interval. The size, construction and orientation of the room were recorded before the researcher left for the day.

Occupants of the monitored room were given the survey forms to fill in during the monitoring. A short explanatory session was given to each household before commencement of monitoring. The Babuc comfort meter, external data logger and the completed forms were collected the following morning.

6.4.8 Thermal votes analysis method

The data from Babuc data logger was downloaded onto a PC and analyzed using Infogap software, the proprietary software for downloading and analysing data from Babuc instruments, and Microsoft Excel 2002 spreadsheet. Data from the HOBO data loggers are downloaded onto a PC and analysed with Excel. The Infogap software provides analysis of all the data from the Babuc sensors and produces additional synthetic data such as operative temperature and mean radiant temperature.

The environmental profiles acquired are then compared with the behavioural data from the completed survey form to draw correlations between the computed data and the actual occupants' responses. The data from each case was then entered into Statistic Program for Social Science (SPSS) version 11.5 (http://www.spss.com) for general analysis.

Several analyses are conducted to establish the neutral temperature for the sample populations. The analysis methods are as follows:

1. Correlation Analysis: A correlation analysis was conducted to establish the relationship between environmental parameters and the thermal votes

2. Revised Griffiths method: the revised Griffiths method discussed in Chapter 3 is used to establish the neutral temperature for the whole air-conditioning sample population, as well as the neutral temperatures for two blanket groups, namely normal blankets and comforters. The revised

method is chosen instead of the original Griffiths method since this method has been proven to be more robust and reflect adaptive influence more strongly [9].

The thermal neutralities are then compared to those established by other studies in the region as well as with the adaptive models explained in section 2.5.3. A problem faced by this is the fact that none of the other field studies produce thermal neutralities for specifically sleeping subjects. However, comparison with these studies helps in establishing general agreement with the finding of others, with allocation for differences due to the different metabolic rate. Analyses of different blanket categories are also conducted to see the effect of different blanket thickness on thermal neutrality.

6.5 Summary

Literature surveys revealed little information on the use of air-conditioning in Malaysian homes. Prior to a thermal comfort field survey, preliminary studies were conducted to establish information on household characteristics, air-conditioner use patterns, general behaviour of occupants and the environmental characteristics of air-conditioned spaces in homes.

The preliminary studies revealed that most domestic units are installed in the bedrooms and are used predominantly during sleeping hours. Following this, a thermal comfort field survey was carried out, adopting a Level 3 investigation according to Nicol's taxonomy [3] in air-conditioned bedrooms monitoring night time occupancy.

The main survey consisted of 29 households with air conditioning and 9 households without air-conditioning. The monitoring period for each case ran from 1800 to 0800 the following day. All environmental data was gathered using a Babuc thermal comfort meter. Thermal sensation votes, use of air-conditioning units, insulation level and the use of ceiling fans were surveyed using self-completed questionnaire.

6.6 References

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PART III: RESULTS AND FINDINGS

7 Results of Preliminary Studies

7.0 Introduction

The data from the preliminary studies are analysed and the results are presented in this chapter. The preliminary household survey provides general information on household characteristics, the operational use pattern of air-conditioners and the general behaviour of occupants in air-conditioned rooms. The preliminary monitoring study shows the environmental conditions of air-conditioned bedrooms over the course of a few days. The findings from these studies help to establish the characteristic of typical air-conditioning use in Malaysian homes. Two of the typical characteristics, i.e the units are installed in the bedrooms and are predominantly used during sleeping hours, provide the focus areas within which the subsequent thermal comfort study investigates.

7.1 Results of household survey

A household survey was conducted on a total of 112 households with air-conditioners. The survey was conducted by enumerators interviewing house owners. This section describes the results of this survey. Another 24 households without air-conditioning were also surveyed as a control group.

7.1.1 House type

The type of dwellings surveyed in this study is shown in Table 7-1 below. In the survey sample, medium cost single storey dwellings form the majority of the sample taken (56%). This is followed by low cost double storey (21%), low cost single storey (14%), Medium cost double storey (5%) and flats (4%).

Table 7-1- Distribution of house types

Housetype	Number	Sample study distribution (%)
Medium Cost single storey terraced	63	56
Low cost Double storey terraced	24	21
Low cost Single Storey terraced	16	14
Medium Cost Double storey terraced	5	5
Flats	4	4
Total	112	100

The result is compared to the information available from national census 2000, It is found that the house types above represent 63% of households in Malaysia [1]

7.1.2 Number of air conditioning units per household

The number of air-conditioning units installed in each household is surveyed and the results are shown in Table 7-2. From the table it can be seen that a cumulative of 85% of the households had 1 or 2 air-conditioning units installed. Only one household has 5 units of air-conditioning installed.

Table 7-2 - Number of air conditioning units per households

Number of units	Frequency	Percent (%)	Cumulative Percent (%)
1	53	47	47
2	42	37	84
3	13	12	96
4	3	3	99
5	1	1	100.0
Total	112	100.0	

7.1.3 Description of air conditioning units

The total number of air-conditioning units in the sample survey was 193. The respondents were asked regarding the description of individual air conditioning units. Among the information gathered was the power of units, location of installation, unit type, frequency of use, control of operation, temperature setting and period of use.

7.1.3.1 Power of units:

The capacity of units is surveyed (in horse power) and the results are shown in Table 7-3. From the table, it can be seen that majority of units are 1hp (750W). This group forms 83% of the sample analysed.

Table 7-3- Power of units (hp)

Power Hp(W)	Frequency	Percent (%)
1 (750)	157	83
1.5 (1025)	21	11

1.8 (1350)	3	2
2.0 (1500)	9	4
Total	190	100.0
Missing	3	

7.1.3.2 Location of units:

Table 7-4 shows the locations of all the units surveyed. It is found that most of the units are installed in the bedrooms; a cumulative 91% and the rest are installed in the living rooms.

Table 7-4 Locations of units

Location	Frequency	Percent (%)	Cumulative Percent
master bedroom	127	66	66
2nd bedroom	45	23	89
3rd bedroom	3	2	91
living room	18	9	100.0
Total	193	100.0	

7.1.3.3 Type of units:

Table 7-5 shows the type of unit surveyed. Most of the units are the single split type system. Only one unit in the sample was found to be of window unit type.

Table 7-5- Type of units

Unit type	Frequency	Percent (%)
split unit	192	99
window unit	1	2
Total	193	100.0

7.1.3.4 Frequency of use:

Respondents were asked regarding the frequency of use of the units. Table 7-6 shows the results. 139 of the units are used everyday (72%). 18 units are used often but not everyday (9%). 36 units are seldom being used (19%)

Table 7-6- Frequency of use

Use	Frequency	Percent (%)	Cumulative Percent (%)
everyday	139	72	72
often	18	9	81
seldom	36	19	100
Total	193	100.0	

7.1.3.5 User control:

Occupants were asked whether or not they use a timer for the operations of the units. Table 7-7 shows the result that most users do not use timers for the operation of the units (72%). Only 55 units were being operated by timers (28%).

Table 7-7- Use of timer

	Frequency	Percent (%)
Manual	138	72
Timer	55	28
Total	193	100.0

7.1.3.6 Period of use (hours)

Respondents were asked regarding the time they normally operate the units during weekdays and weekends. During interviews, actual hours of normal operation were marked on a 24-hour disc diagram (see appendix 2). For the purpose of analysis, the number of hours are then counted and binned into four periods of operation. The first period runs from 6 am in the morning to midday. The second period runs from midday to 6 pm, the third period from 6 pm to midnight, and the fourth period runs from midnight to 6 am. The total hours are then averaged for each period.

Table 7-8 shows the time of operation during weekdays use. This information is only available for 172 of the units. It was found that during weekdays, the fourth period 0000 to 0600 is the time when the units are used the most, with an average operation of 4 hours. This is followed by 1800 to 0000 (2.2 hours), then 0600 to 1200 (0.8 hour) and last 1200 - 1800 (0.4 hour).

Table 7-8 - Time of operation of units during weekdays

Time	N	Minimum (hours)	Maximum (Hours)	Mean (hours)	Std. Deviation (hours)
0600-1200	172	0.0	6.0	.8	1.8
1200-1800	172	0.0	4.0	.4	1.0
1800-0000	172	0.0	6.0	2.2	1.5
0000-0600	172	0.0	6.0	4.0	2.4

Since most Malaysians do not work on Saturdays and Sundays, a separate analysis was conducted to see the difference in the use pattern of the units. For analysis, the weekend period is defined as the time starting 12 am Saturday to 12 am Monday. Table 7-9 shows the time of operation during weekends.

Table 7-9- Time of operation of units during weekends

Time	N	Minimum (hours)	Maximum (Hours)	Mean (hours)	Std. Deviation
0600-1200	172	.0	6.0	1.1	2.0
1200-1800	172	.0	4.0	0.6	1.2
1800-0000	172	.0	6.0	2.2	1.5
0000-0600	172	.0	6.0	4.1	2.3

From the table it can be seen that during weekends the pattern is similar to that of weekdays. However the numbers of hours of use are slightly higher. During weekends, 0000 to 0600 is the time when the units were used the most, with an average of operation of 4.1 hours. This is followed by 1800 to 0000 (2.2 hours), 0600 to 12000 (1.1 hour) and 1200 to 1800 (0.6 hour).

The number of cases where the units were being used the whole time during each time period (6 hours) was also analysed. **Error! Reference source not found.** shows the result. It was found that the highest number of cases where the units being used for the whole period is between 12pm and 6am, where 94 cases (49% of the units) during weekdays and 100 (52%) of the units) cases during weekends are found.

Table 7-10 Cases using AC units the whole time for each period of analysis

Time	No of units (%)	
	Weekdays	Weekends
0600-1200	12 (6)	15 (7.8)
1200-1800	0 (0)	0 (0)
1800-0000	6 (3)	6 (3)
0000-0600	94 (49)	100 (52)

It is necessary to investigate whether there's a difference between use pattern during weekdays and weekends, since it can be expected that people spend more time at home during weekends. The average number of operations during weekdays and weekends is shown in Table 7-11 below. On average air-conditioners are used 7.7 hours during weekdays and 8.2 hours during weekends. However the difference is found not to be significant (p=0.608).

Table 7-11 Hours of operation (weekdays and weekends)

	Day type	N	Mean	Std. Deviation	Std. Error Mean
HOURS	weekdays	11	7.7	3.2	.98
	weekends	96	8.2	5.92	.60

p=0.608, p>0.05

7.1.4 Behavioural characteristics

During the interview for each household, two respondents using the air conditioning units were asked questions relating to their behaviour during the use of air-conditioning units. A total of 89 males and 77 females were interviewed during the survey of the main group. For the non air-conditioned group, 14 male and 10 female were interviewed, giving a total sample population of 190 (Table 7-12). The mean age for the sample is 42.5 years old.

Table 7-12: Distribution of gender of sample population

Gender	Main group	Control group	Total
Male	89	14	103
Female	77	10	87
Total	166	24	190

7.1.4.1 Use of coverings during the night:

To understand their use of covering during the night, respondents were asked the question "How do you normally use your blanket during the night?" This question covers all type of blankets, regardless of their thicknesses. Table 7-13 shows the results.

Table 7-13- Use of blanket

	AC		Non AC	
	Frequency N	Valid Percent (%)	Frequency N	Valid Percent (%)
No covering at all	29	19	13	54
Blanket used certain times	56	37	9	38
Blanket used all night	68	44	2	8
Total	153	100	24	100.0
Missing	13			
Total	166			

It is found that in most air–conditioned cases, subjects use blankets all night long (44%). 19% of the subjects do not employ the use of a blanket at all. It is possible to suggest that this portion of the sample studied managed to operate their air conditioners to perform satisfactorily during sleeping hours.

The results for the control group show a different pattern of use, the majority of those in this group do not use blanket during sleeping hours. (54%)

7.1.4.2 Thickness of Blanket:

Respondents were asked questions regarding the thickness of the blankets they used. Two categories of blanket thickness were established. Normal blankets are made of single ply fabrics, while comforter refers to 'quilt' type coverings. This type of covering is new in Malaysian domestic use. It consists of filling, normally polyester wool, sandwiched between two layers of synthetic fabrics (see section 5.6.2). Table 7-14 shows the results.

It is found that comforter type blanket forms the most common type used in the air-conditioned group with 54 cases (35%). Comparing the results with those of the non air-conditioned group, the main difference is the absence of the use of comforter in all cases.

Table 7-14- Blanket types

	AC		Non AC	
Blanket types	Frequency N	Percent (%)	Frequency	Percent (%)
No blanket	29	19	13	54
Normal	70	46	11	46
Comforter	54	35	0	0
Total	153	100	24	100.0
Missing	13			
Total	166			

7.1.4.3 Thermal Sensation Vote:

Respondents were asked how they generally feel when air-conditioners are in use in the bedrooms. The answers were cast on the ASHRAE 7 point sensation scale. For the non air-conditioned group, they were asked the general sensation they felt during occupancy of the bedroom (without specifying which period of the day). The results are shown in Table 7-15 and Figure 7-1.

Table 7-15- distribution of thermal sensation votes

Temperature sensation vote	AC		Non AC	
	N	(%)	N	(%)
cold	9	6	0	0
cool	23	15	0	0
slightly cool	75	49	1	4
ok	46	30	13	54
slightly warm	0	0	9	38
warm	0	0	1	4
Missing	13		0	
Total	166	100	24	100

From the table and the graph it can be seen that in air-conditioned cases, the votes are clustered on the colder side of the scale, with majority of the vote cast on '"slightly cold" sensation. In the control cases, the votes are distributed on the warm side of the scale, centering between "ok" to "slightly warm".

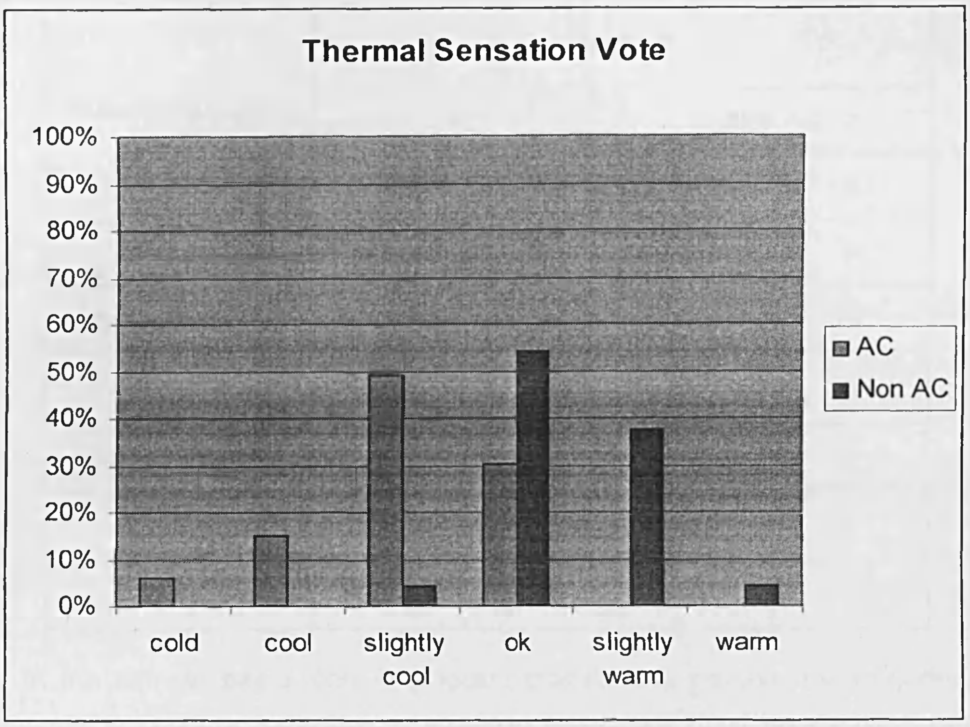

Figure 7-1 : Distribution of thermal sensation votes

The mean vote for both groups is shown in Table 7-16. The mean vote for the main group is - 0.60, while the mean vote for the control group is 0.87. T-test analysis shows that the difference was found to be significant within 99% confidence interval (p = 0.000). This finding suggests that when air-conditioners are used, people generally feel slightly cold. Without the air-conditioners, people generally feel slightly warm.

Table 7-16- Thermal sensation votes: Descriptive Statistics

	GROUP	N	Mean	Std. Deviation	Std. Error Mean
Thermal sensation vote	AC	153	-0.97	.83	0.07
	Non AC	24	0.42	.65	0.13

(P = 0.000)

7.1.4.4 Humidity Sensation Vote:

Respondents were asked to cast votes on the humidity sensation they generally feel when the rooms are air-conditioned. Similar question was asked to the control group regarding the occupancy of a room without air conditioning. 5 point symmetrical Likert scale was used for the votes. Table 7-17 and Table 7-18 show the results.

Table 7-17- Humidity sensation votes

Humidity sensation vote	GROUP			
	AC		Non AC	
	N	(%)	N	(%)
Humid (2)	0	0	0	0
Slightly humid (1)	3	2	7	29
Ok (0)	126	81	16	67
Slightly dry (-1)	22	14	1	4
Dry (-2)	5	3	0	0
Total	156	100	24	100

In the sample population, it is found that in both groups, the majority of the respondents expressed neutrality in humidity sensation (81% and 67%). This is in agreement with the findings by Fountain et.al. [2], that at sedentary activity level, people have low sensitivity to humidity variation. However, the air-conditioned group has higher percentage in the slightly dry and dry category while the non air-conditioned group has higher percentage in the slightly humid category (29%).

Table 7-18- Humidity sensation votes- Descriptive statistics

	GROUP	N	Mean	Std. Deviation	Std. Error Mean
Humidity sensation vote	AC	156	-.19	.50	.04
	Non AC	24	.25	.53	.11

(P = 0.000, p<0.01, difference is significant to 99% level)

The mean humidity vote for the main group is - 0.19, while the mean humidity vote for the control group is 0.25. This finding implies that the use of air-conditioners results in drier conditions felt by occupants T-test analysis was carried out to investigate the difference (P = 0.002). The difference was found to be significant within 99% confidence interval.

7.1.4.5 Use of auxiliary fan

In both cases (main and control), options to use forced convection are available in the form of ceiling, table or standing fans. The use of these fans during the operation of the air-conditioning units was investigated in the survey. Respondents were asked whether they use these fans concurrently when they are using air-conditioning units. For the non air-conditioned group, they were asked the use of ceiling fan during occupancy period. The result is shown in Table 7-19 below. From the survey, it is found that most of the respondents never used auxiliary fans during the operation of their air conditioning units (70%).

Table 7-19- Use of auxiliary fans

Use of ceiling fan	GROUP			
	AC		Non AC	
	No.	Valid Percent (%)	No.	Valid Percent (%)
always	9	6	23	96
often	17	12	1	4
seldom	17	12	0	0
never	102	70	0	0
Missing	21	-	-	-
Total	166	100.0%	24	100.0%

From the survey it can be seen there is a difference in the use of auxiliary fans between the main sample and the control group. As expected, a majority of the control group always use auxiliary fans. An interesting finding is that around 18% of the air-conditioned group always or often uses auxiliary fans. The reason for this is worth looking into. Possible explanations are, in these cases the units could not achieve low enough temperature for the required comfort, hence the need for supplementary cooling by means of forced convection. It is also possible that people prefer to have higher air temperature with convective cooling to achieve comparable cool sensation produced by colder temperature cooling alone, as colder air temperature may results in undesirably drier condition.

7.1.4.6 Adjustment to cold sensation

Respondents in the air-conditioned cases were asked the actions they normally take when they feel uncomfortably cold. Most of the respondents revealed that they would simply turn off the units if they feel too cold (35%). Around 26% said they would adjust the temperature setting and 24% said they would turn off the units and use auxiliary fans instead. Table 7-20 shows the results.

Table 7-20- Adjustment to cold sensation

Adjustment action	Frequency	Valid Percent (%)
Seldom too cold	8	6
Adjust Temperature	38	27
use more covering	9	6
switch off and use auxiliary fan	36	26
turn off unit	49	35
Total	166	100.0
Missing	26	-

7.1.4.7 Satisfaction with the units

Respondents were also asked whether they are satisfied with the units. The satisfaction in question relates to the objective of their use, i.e. to provide comfort and this exclude energy efficiency issues. The result is shown in Table 7-21 below. It is found that majority of respondents are satisfied with their air-conditioning units.

Table 7-21 Satisfaction with the units

Satisfied with the performance of the units	Frequency	Percent (%)
yes	107	95
no	2	2
missing	3	3
Total	109	100

7.2 Summary and analysis of household survey

The purpose of the above survey is to establish the characteristics of air-conditioner use in homes. Among issues investigated were the use pattern and description of units, the characteristics of the households and the characteristics of users' behaviour, both in the use of the units and other measures adopted to achieve comfort in air-conditioned bedrooms. It was found that:

7.2.1 System characteristics

- The majority of the houses have 1 unit installed. Most of the units are located in the master/main bedroom (6%). Around 23% are located in the 2nd bedroom and only 18 units (9%) are located in the living area.
- Majority of the units are of 1hp (750W) which form 83% of the units surveyed, this is followed by 1.5hp (1125W) units (11%), 2hp (1.5kW) units (4%). Only one case of unit having 1.8hp (1.6%).
- Most of the units are of split unit type (99%). Only 1 unit surveyed was a window type unit (2%).

7.2.2 Operational patterns

- Most of the units are used everyday (72%). Around 9% of the units are used frequently. Around 18.7% are seldom used.
- An analysis of the control operation reveals that most of the units are controlled manually (72%) with only 28% controlled by a timer.
- There is a small difference found in the period of use during weekdays and weekends, with weekend use being slightly greater. The period when the units are used the most is between midnight and 6 am in the morning. This is followed by the period between 6pm and midnight. This is due to the fact that the room is used during the night and mostly over sleeping hours.

7.2.3 Adaptive behaviour

- The use of comforter, the thickest form of covering, can only be found in the air conditioned group (35%) while no one in non air conditioned rooms use them.
- When asked about temperature sensation, occupants using air-conditioners were found to have an average thermal sensation vote of -0.6. (Slightly cold). This condition is found to be just outside the lower comfort boundary for 10% PPD as suggested in ISO 7730 [3], i.e. - 0.5 PMV. The temperature sensation vote in the control group is 0.9, which is also beyond the ISO recommendation but on the warmer side.

- The general humidity sensation vote of the main group is slightly on the dry side (-0.19). The control group indicates a slightly humid sensation (0.25)

- From the survey, it can be concluded that the use of forced convection by means of auxiliary electric fans is reduced when air-conditioning is available.

- Subjects are asked how they adjust to having a cold sensation. 35% said they just turn off the unit. Around 27% said they would adjust the thermostat setting. 26% said they would turn off the unit and switch on ceiling fan instead. Only 6% said they seldom felt too cold. Considering most units are used during the night, and daytime use does not really get too cold, we can assume that people have to wake up during the night to make these adjustments. Verbal conversations with a few subjects reveal that this is actually the case. One of the subjects said that it is his normal practice to wake up at around 3am to 4am in the morning to switch off the unit as it got too cold by then. Interestingly 96% of respondents say that they are satisfied with their air-conditioning units. This indicates people are ready to take adaptive adjustments and feel satisfied with the thermal conditions.

The household survey managed to highlight several key issues, which deserve more detailed study. Three most important findings of this survey, which have immediate implication on the focus of the work, are:

1. *Most air-conditioning units are used in the bedroom*
2. Most are operated during the night, especially during sleeping hours.
3. An indication was found that in many cases people have to wake up to carry out adjustment of the operation of their units <u>during</u> normal sleeping hours.

Following the household survey, a monitoring study of bedrooms with air-conditioning units was conducted. The results of the monitoring study are discussed in the following sections.

7.3 Results of monitoring non-air-conditioned bedrooms

Following the household survey, a monitoring study was conducted. Two sets of monitoring were conducted. First, the thermal conditions of four non-air-conditioned houses were monitored over a few days. Then 7 households with air-conditioned bedrooms were monitored. The results of both studies are then compared.

Table 7-22 below shows the summary of the non air-conditioned houses monitored in this study. The maximum daytime temperature and the minimum night time temperature for each case are shown in Table 7-23. Table 7-26 highlight the average, daytime and night time internal and external temperatures found.

Table 7-22 Summary of non- air-conditioned houses studied in preliminary monitoring survey

Case name	Location	House type	Construction type	Date of monitoring
C01	No 8, Jln Kemuning Kelang	Single storey terraced	Masonry	11-12/01/ 2003
C02	Taman Bangi	Two storey terraced	Masonry	2-3/01/03
C03	Kampung Sri Tanjung	Single storey Bungalow	Masonry	27-28/1/03
C04	Kampung Sri Tanjung	Single storey Bungalow	Timber	27-28/1/03

Table 7-23 Average temperature and humidity of non-air-conditioned houses

	C01		C02		C03		C04	
	Internal	External	Internal	External	Internal	External	Internal	External
Ave night time temp (°C)	28.5	27.1	29.2	27.4	29.5	27.4	27.6	27.5
Ave daytime temp (°C)	28.2	27.4	29.2	29.1	30.0	29.0	29.2	29.0

Figure 7-2 to Figure 7-5 show the psychrometric results of all the studies. The comfort zone proposed by ASHRAE [4], Abdulshukor [5] and Szokolay [6] are plotted on the same chart to provide comfort evaluation analysis.

In general the internal conditions of all the houses were characterised by consistently high temperatures and high humidity. Apart from the timber house, it is found from the study of all houses that the internal conditions of the bedrooms were higher than the external conditions especially during the night time. In general the thermal mass of masonry construction has the effect of reducing temperature fluctuation.

In all cases, where the external condition does not fall within the comfort zone as suggested by Abdulshukor[5] for Malaysia, the internal conditions of the bedrooms too do not fall within the same comfort zone. However, when the effect of the use of ceiling fans is taken into account, the conditions largely fall within the comfort zone suggested by Szokolay [6] for air velocities of 1m/s and 1.5m/s.

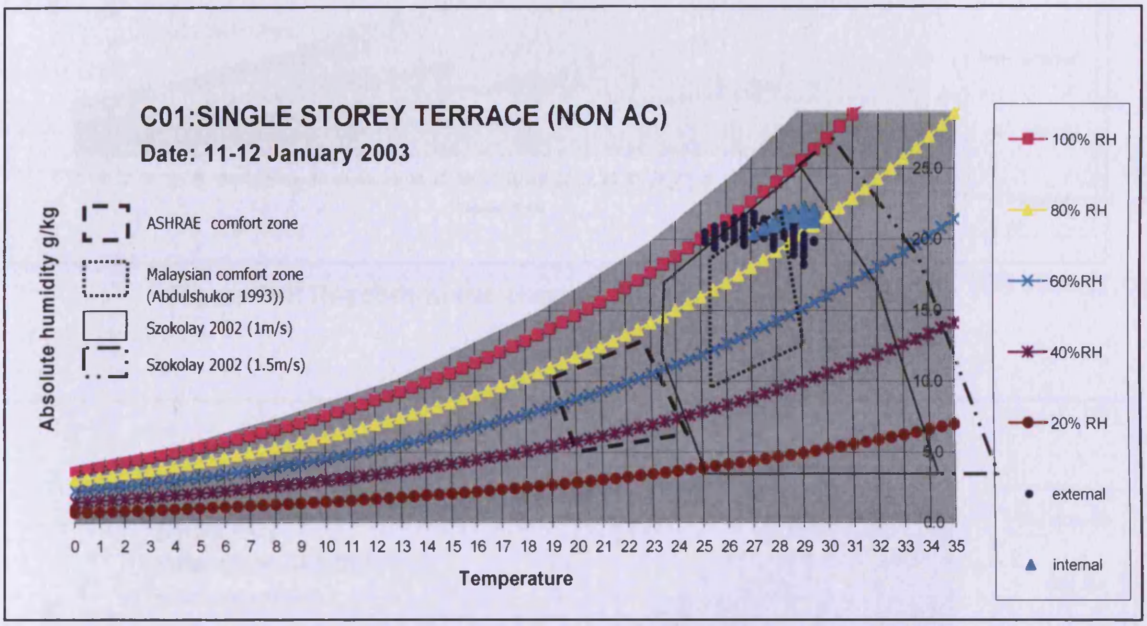

Figure 7-2: Psychrometric chart of C01 (single Storey Terrace)

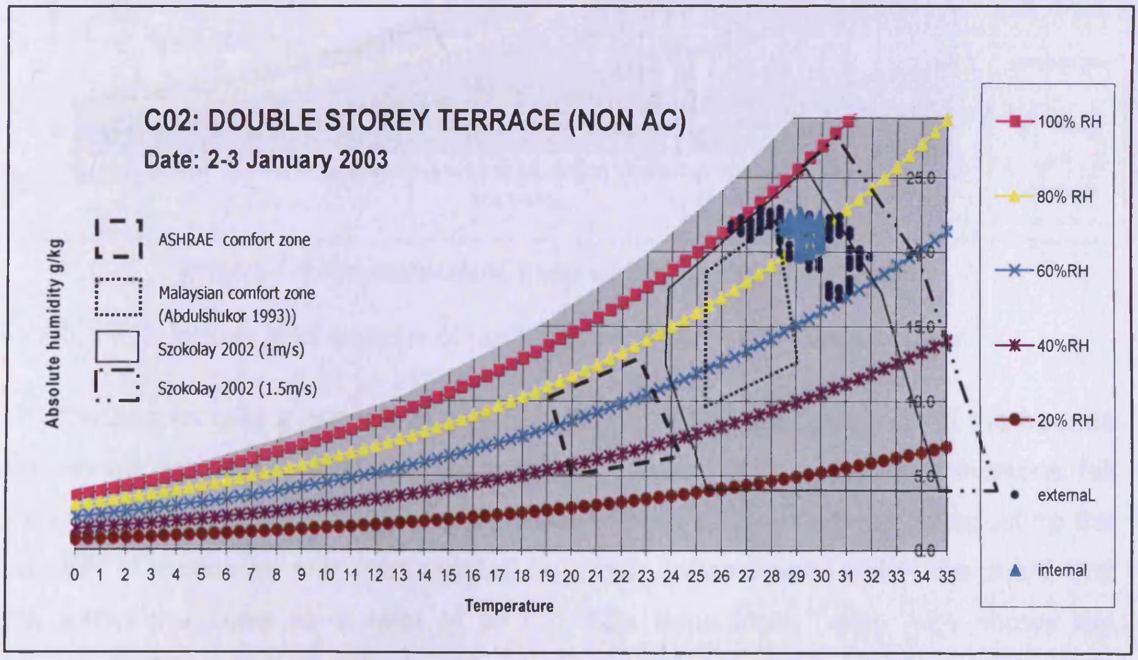

Figure 7-3: Psychrometric chart of C02 (Double Storey Terrace)

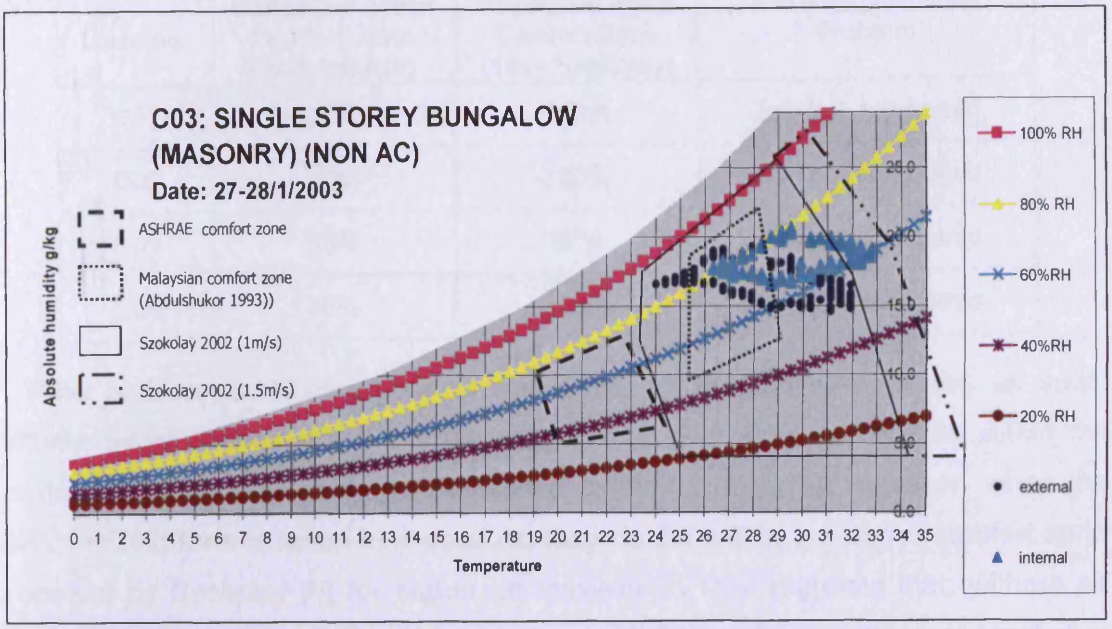

Figure 7-4: Psychrometric chart of C03 (Bungalow - Masonry)

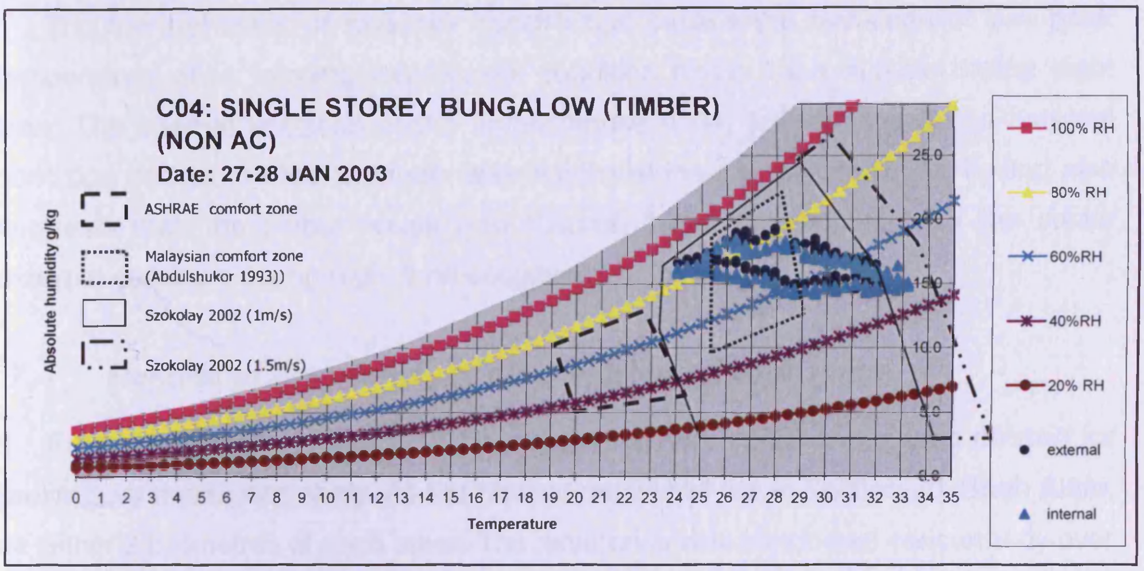

Figure 7-5: Psychrometric chart of C01 (Bungalow - Timber)

7.3.1 Summary and analysis of monitoring non air-conditioned houses

The results give a general picture regarding the internal conditions of the houses monitored. For each case, the percentage of time that the internal conditions fall within the comfort zone suggested by Abdulshukor was carried out by counting the number of measurements (represented by a blue triangle point within the chart) that fall within the zone as a ratio of all the data measured. Table 7-24 shows the summary of the monitoring survey of non air-conditioned rooms.

Table 7-24 Summary of monitoring survey of non air conditioned rooms

Case no.	Conditions within Comfort Zone (Abdulshukor)	Conditions within Comfort Zone (1m/s Szokolay)	Extreme conditions Problem
C01	30%	100%	Too hot, too humid
C02	1%	100%	Too hot, too humid
C03	30%	80%	Too hot, too humid
C04	40%	100%	Too hot, too humid

The environmental conditions of these houses can be summarised as such: Without air conditioning, the internal condition of bedrooms hardly falls within the comfort zone for Malaysians as developed by Abdulshukor[5]. However, when the use of ceiling fans is taken into account, they do fall within the larger comfort zone proposed by Szokolay [6] for higher air movement. This suggests that, without air conditioning, the use of ceiling fan is indispensable in achieving thermal comfort in Malaysian house.

The thermal mass of masonry construction causes the reduction of day peak temperature while keeping the internal condition higher than outside during night time. The internal condition of the timber house (C04) follows closely the external condition due to the low thermal mass nature of the construction. The finding also suggests that, the timber house (low thermal mass) can benefit from the colder external condition during night time occupancy.

7.4 Results of monitoring of air-conditioned bedrooms

From the household survey, 7 households with air-conditioning were chosen for preliminary monitoring study. All the houses monitored are in Section 20, Shah Alam, all within 2 kilometres of each other. The monitoring was conducted concurrently over 7 day's period, from 26th October 2003 to 1/11/2003. Table 7-25 below shows the summary of the households monitored in this survey.

Table 7-25 Summary of household monitored (with air-conditioning)

Monitoring no:	Location	House type:	Date of survey:
M01	Seksyen 20, Shah Alam	Low cost single storey	26/10 – 1/11/03
M02	Seksyen 20, Shah Alam	Medium Cost Single Storey	26/10 – 2/11/03
M03	Seksyen 20, Shah Alam	Medium cost double storey	26/10 – 1/11/03

M04	Seksyen 20, Shah Alam	Low cost single storey	26/10 – 1/11/03
M05	Seksyen 20, Shah Alam	Medium cost single storey	27/10-2/11/03
M06	Seksyen 20, Shah Alam	Medium cost single storey	26/10 – 1/11/03
M07	Seksyen 20, Shah Alam	Medium cost single storey	25/10 – 31/10/03

The period between 2200 on 28/11/03 and 0400 on 29/11/03 is selected for average condition data. The reason being, during this period all the houses use their air conditioning units, hence comparative analysis is possible due to similar external conditions. The data during this period are also charted onto psychrometric charts.

As with the non air conditioned cases, the percentage of time that the conditions fall within the comfort zone suggested by Abdulshukor was carried out by counting the number of measurements that fall within the zone. The sensation vote and humidity vote cast by occupants are also shown for each case. Table 7-26 shows the summary of the analysis conducted from the monitoring data. The results show that three houses have less than 50% of the measurements within the comfort zone. House M01 has the most problems with less than 1% of its condition matches that of the comfort zone. In all three cases the resulting condition is too cold and too dry. The sensation vote and humidity vote cast by occupants are also shown for each case.

Table 7-26 Summary of monitoring survey of air conditioned rooms

Case no.	Conditions within Comfort Zone (Abdulshukor)	Extreme conditions Problem	General Temperature sensation Vote	General Humidity Vote
M01	< 1%	Too dry, Too cold	Slightly Cold	Ok
M02	100%	-	Ok	Dry
M03	%90	-	Ok	Ok
M04	%45	Too dry, Too cold	Slightly Cold	Ok
M05	%10	Too dry, Too cold	Ok	Ok
M06	%60	-	Slightly Cold	Ok
M07	60%	-	Ok	Dry

It can be seen that some of the occupants thought the condition was slightly cold and slightly dry. Figure 7-6 to Figure 7-12 shows the average conditions of all houses plotted on psychometrics charts. It is found that the average condition falls largely within the comfort zone (approx 85%).

7.4.1 Summary and analysis of monitoring study of air-conditioned houses

The psychrometric analysis of all cases is shown in Figure 7-6 to Figure 7-12. The results shows that the internal conditions of air-conditioned rooms monitored in this study do not fall within the comfort zone suggested by ASHRAE except in one case (M04). However when the comfort zone for Malaysian suggested by Abdulshukor is used, the condition shows approximately 85% match, indicating satisfactory internal conditions.

The actual internal conditions are found to fluctuate with the external condition. This can be attributed to two problems:

1. Inadequacy of unit power rating (due to underestimation of cooling load or simply wrong choice of unit power rating during installation)
2. Less than optimum performance of the unit due to poor maintenance.
3. The leakiness of the room. (High air infiltration rate)

Summary of the results from the preliminary monitoring campaign is shown in Table 7-27.

Table 7-27 Summary of monitored houses

Case no:	M01	M 02	M03	M04	M05	M06	M07
Room	Master bedroom	Master bedroom	Master bedroom	Master bedroom	Master bedroom	Living room	Master bedroom
House category:	Low cost single storey	Medium Cost Single Storey	Medium cost double storey	Low cost single storey	Medium cost single storey	Medium cost single storey	Medium cost single storey
Power of unit	1	1	1	1	1	1	1
Temperature setting	19C	26C	17C	22C	18C	20C	25C
Fan Setting	medium	Low	-	-	Medium	Low	Medium
Satisfaction	yes	yes	yes	-	Yes	yes	yes
Ceiling fan	no	no	no	no	no	often	no
Temp vote	Slightly Cold (-1)	Ok(0)	Ok(0)	Slightly Cold (-1)	Ok(0)	Slightly Cold (-1)	Ok(0)
humidity vote	Ok(0)	Dry (1)	Ok(0)	Ok(0)	Ok(0)	Ok(0)	Dry (1)
Min Temp (°C)	26.3	26.3	26.3	22.9	26.0	27.1	27.5
Max Temp (°C)	28.7	27.9	29.1	30.3	29.9	29.9	29.9
Ave Temp (°C)	27.2	26.8	27.5	24.8	27.0	28.2	28.3
Min Humidity	78.8	59.3	46.4	42.7	34.5	65.8	45.9
Max Humid	91.7	78.2	71.9	68.2	55.4	79.8	71.2
Ave Humid	86.9	71.7	57.4	45.3	37.7	70.3	53.0

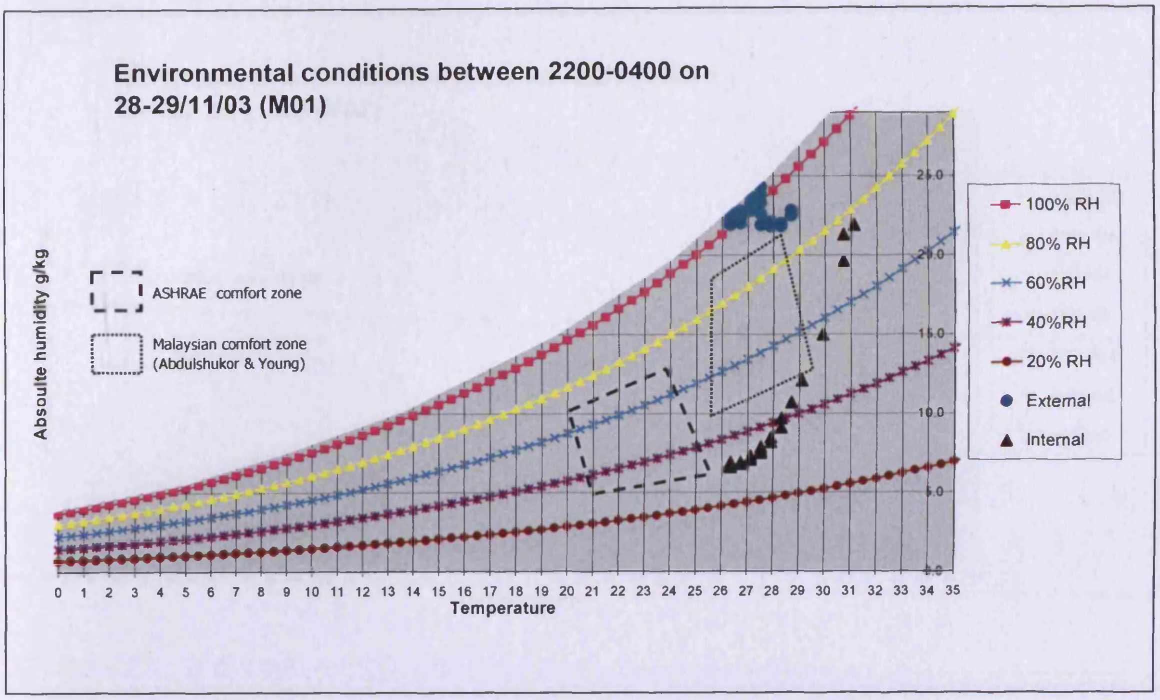

Figure 7-6: Psychrometrics of case M01

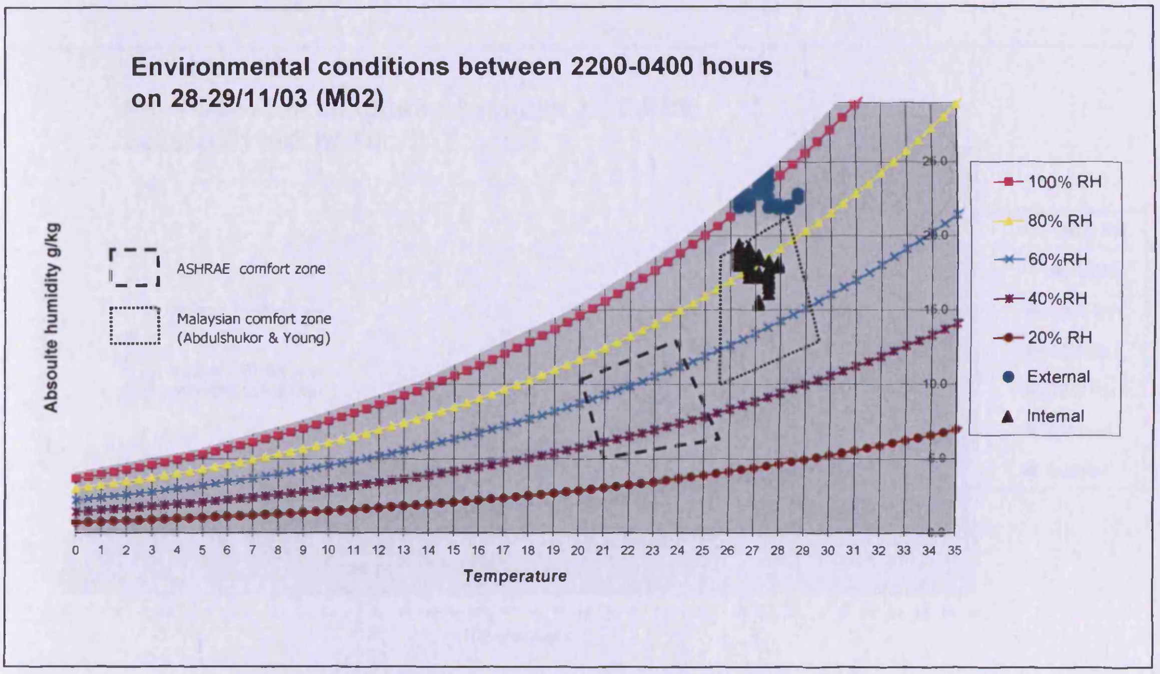

Figure 7-7: Psychrometrics of case M02

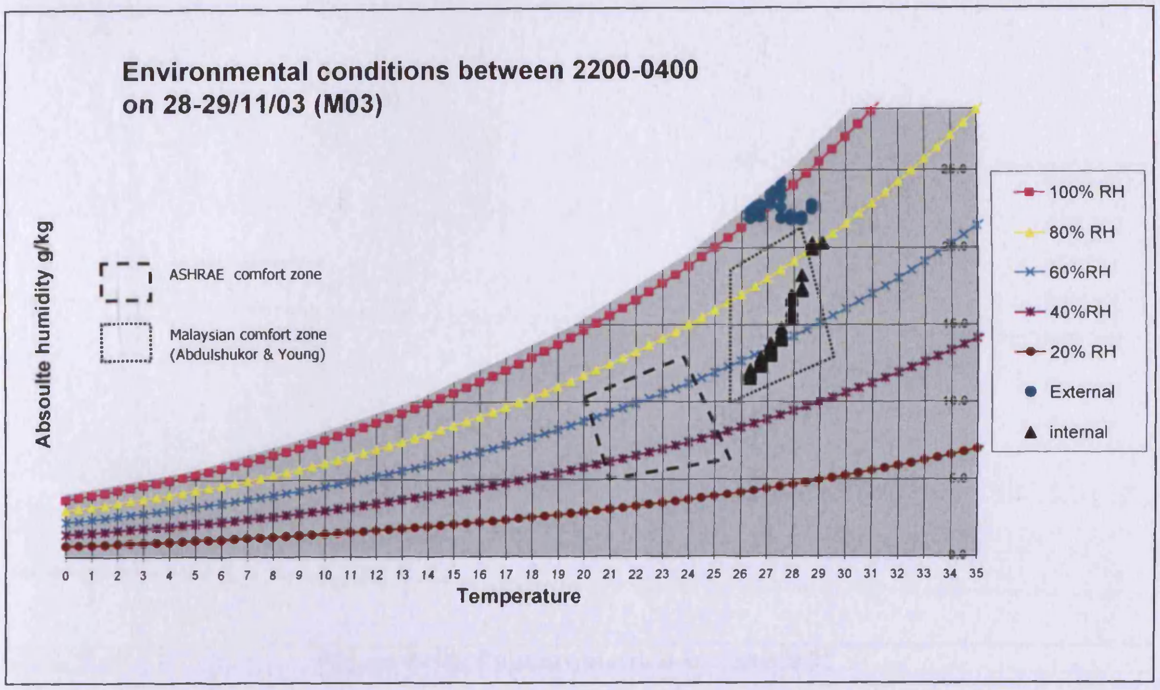

Figure 7-8: Psychrometrics of case M03

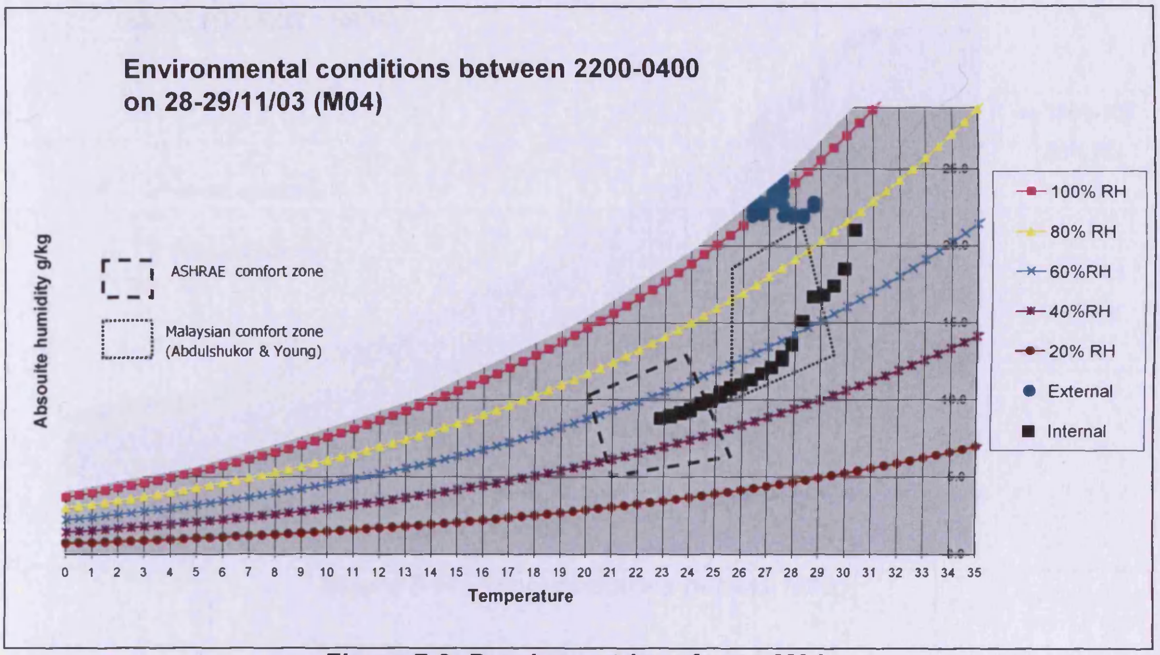

Figure 7-9: Psychrometrics of case M04

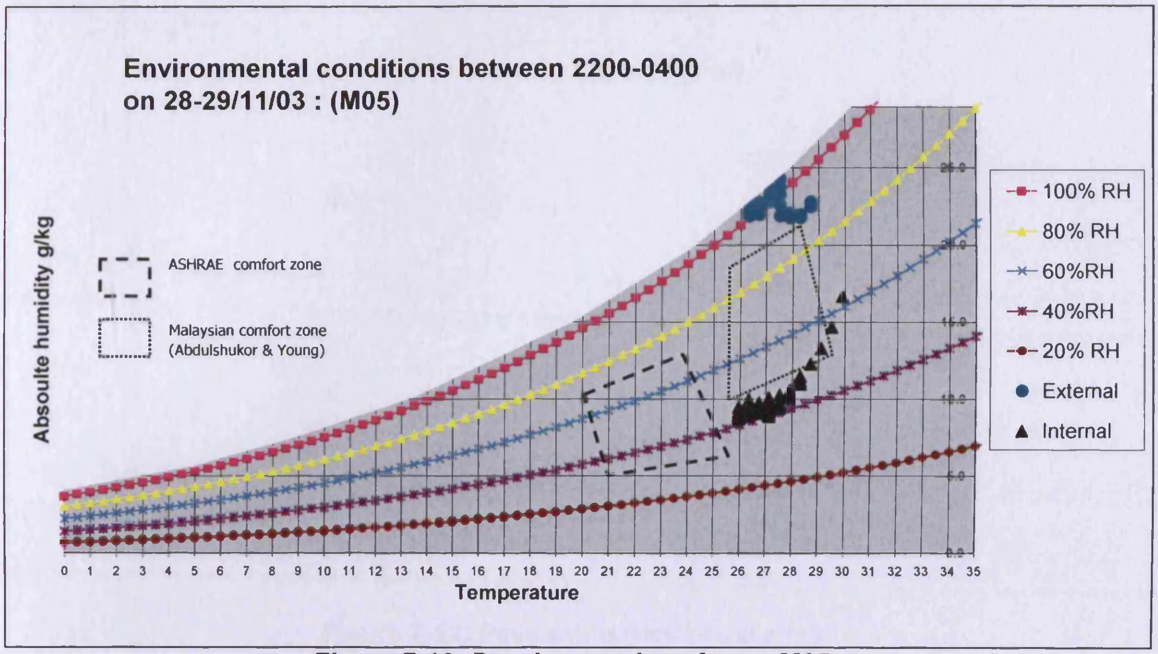

Figure 7-10: Psychrometrics of case M05

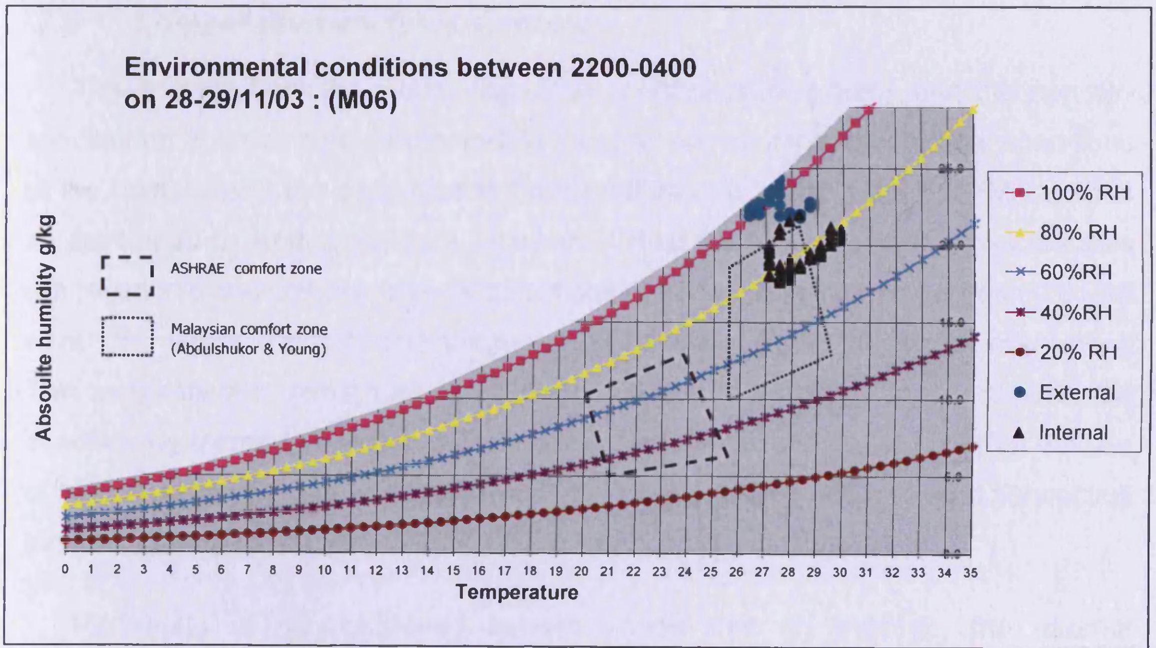

Figure 7-11: Psychrometrics of case M06

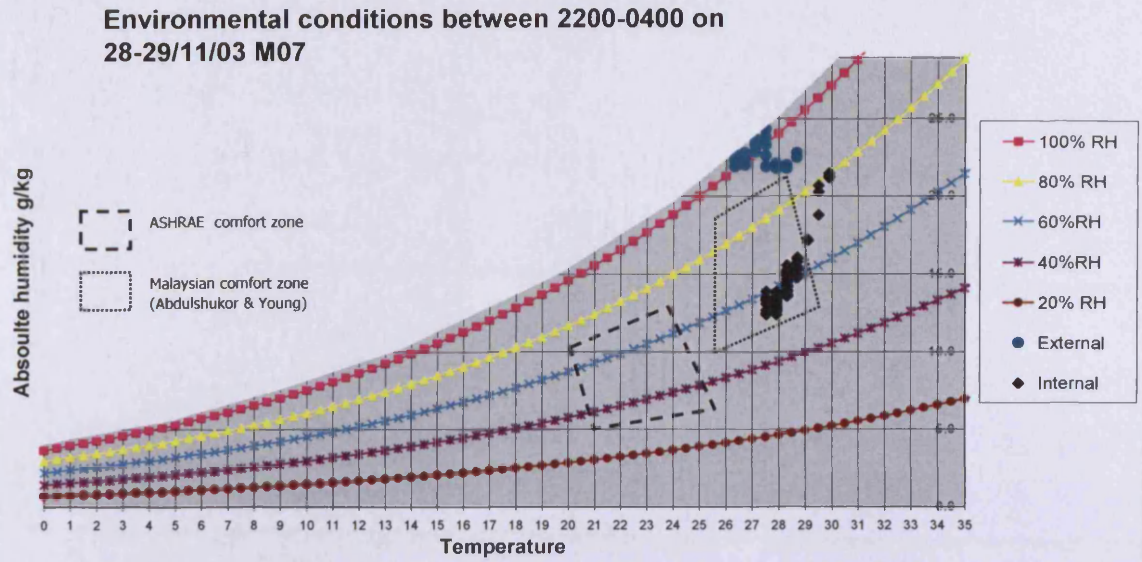

Figure 7-12: Psychrometrics of case M07

7.5 Comparative analysis summary

The findings from the monitoring of air-conditioned bedrooms and the non air-conditioned bedrooms are compared. Without air conditioning, the internal conditions of the bedrooms in the case studies hardly fall into the comfort zone for Malaysians as developed by Abdulshukor [5]. However, When the use of forced convective fans are taken into account, the internal conditions of non air-conditioned bedrooms do fall within the larger comfort zone proposed by Szokolay [6] for higher air movement. This suggests that, without air conditioning, the use of a ceiling fan is indispensable in achieving thermal comfort in a Malaysian house. It can also be argued that the use of air-conditioners is not a must in Malaysian homes, as the use of forced convective fans can provide occupants with a satisfactory comfort condition.

Monitoring of air-conditioned houses shows that on average, the internal conditions do fall within the comfort zone suggested by Abdulshukor. However in some cases the conditions can be too cold and too dry.

7.6 Summary

The preliminary studies set out to establish important information regarding the use of air-conditioners in Malaysian homes, which are not available in the literature. The findings also highlight as an area of importance, the study of thermal comfort in air-conditioned dwellings.

From the preliminary studies, it is established that aspects needing further investigations are bedrooms and the period during night time occupancy. The subsequent field survey study therefore focuses on these aspects. An indication is found that some users might have to interrupt their sleep to carry out adjustment to the operations of the air conditioning units.

Monitoring of household without air conditioning was also conducted for comparative purpose. It is worth mentioning that it is possible to achieve comfort with higher air movement, by employing fans. This is actually still the norm in Malaysia. This mode of cooling can be a better alternative since the resulting energy need for cooling is lower than that of air-conditioning.

Monitoring of air conditioned houses revealed that the use of air conditioning helps in bringing the internal condition into the comfort zone for Malaysians. However in some cases, evidence of overcooling and dryness is found.

7.7 References

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8 Results of field survey: Environmental conditions and occupant behaviour

8.0 Introduction

Following the analysis of the general survey conducted in Chapter 7, a thermal comfort field survey was conducted on selected households within the Klang Valley. A total of 29 bedrooms with air-conditioners and 9 bedrooms without air-conditioners were monitored. In the field survey, the information on the characteristics of the units, use pattern, occupant behaviour and thermal votes was acquired. The analysis of the field survey is divided into three sections:

<u>Environmental conditions analysis</u>: this includes analysis of the environmental variables such as temperatures, humidity and air movement. Also included is the thermal profile analysis of each case, i.e. the variation in the thermal conditions throughout the monitoring period.

<u>Adaptive behaviour analysis</u>: This covers the operation of air-conditioning units, e.g. the temperature setting chosen by occupants, the duration of use, adjustment type, use of auxiliary fan, clothing level, blanket thickness and use.

<u>Thermal comfort analysis</u>: this is conducted by analysing the relationship between environmental data and the thermal votes cast by occupants. Neutral temperature and comfort range is established in this analysis.

This chapter discusses the results of the first two sections of the analysis. The thermal comfort analysis is discussed in the next chapter.

8.1 Case descriptions

The types of the houses investigated in the survey are shown in Table 8-1 below. A total of 29 houses with air-conditioned bedrooms were monitored. Another nine houses without air-conditioning units were monitored to serve as control group. All the houses are of masonry constructions and similar to the types of houses discussed in the literature.

Table 8-1 House types distibution

<table>
<tr><th rowspan="2">House type</th><th colspan="2">Main</th><th colspan="2">Control</th><th rowspan="2">National urban weight* (%)</th><th rowspan="2">National weight* (%)</th></tr>
<tr><th>No</th><th>Percent (%)</th><th>No</th><th>Percent (%)</th></tr>
<tr><td>Single storey terraced</td><td>5</td><td>17</td><td>2</td><td>22</td><td rowspan="2">54</td><td rowspan="2">41</td></tr>
<tr><td>Double storey terraced</td><td>15</td><td>52</td><td>2</td><td>22</td></tr>
<tr><td>Detached</td><td>3</td><td>10</td><td>3</td><td>33</td><td>25</td><td>42</td></tr>
<tr><td>Apartment</td><td>6</td><td>21</td><td>2</td><td>22</td><td>18</td><td>11</td></tr>
<tr><td>Total</td><td>29</td><td>100.0</td><td>9</td><td>100.0</td><td>97</td><td>94</td></tr>
</table>

Source: National Housing and Population Census 2000. Dept. of Statistics, Malaysia

All the houses monitored in the study are located in urban areas. In 2000, 53% of Malaysian households are in urban areas [1]. The national weight distributions of the house types in urban area are shown in the right hand column. It can be seen that the house types monitored in this study represent 97% of urban households in Malaysia.

8.2 Environmental conditions

This section describes the internal and the external environmental conditions found during the monitoring. For the internal conditions, the data analysed are only those acquired while the air conditioning units were being used.

8.2.1 External conditions

The external conditions throughout the monitoring period of each case are analysed. The external conditions were recorded by the Hobo data logger, placed outside the house during monitoring. The variables measured were air temperature and relative humidity, recorded at 5 minutes interval. Table 8-2 below shows the minimum, average and minimum values of external ambient conditions during the monitoring period, from 6pm to 8am the next morning.

Table 8-2: External conditions throughout monitoring period (6pm-8am)

	Minimum	Maximum	Mean	Std. Deviation
Average external temperature (°C)	25.1	30.3	27.8	1.3
Average external humidity (%)	38.1	95.1	74.5	16.47

A look into the external air temperature profiles reveals that the temperature gets cooler from 6 pm to 8 am the next morning. The warmest measurement recorded is 31.5°C and the coldest is 24.4°C. The standard deviations in all cases are fairly small. Figure 8-1 shows a typical external temperature profile during monitoring period.

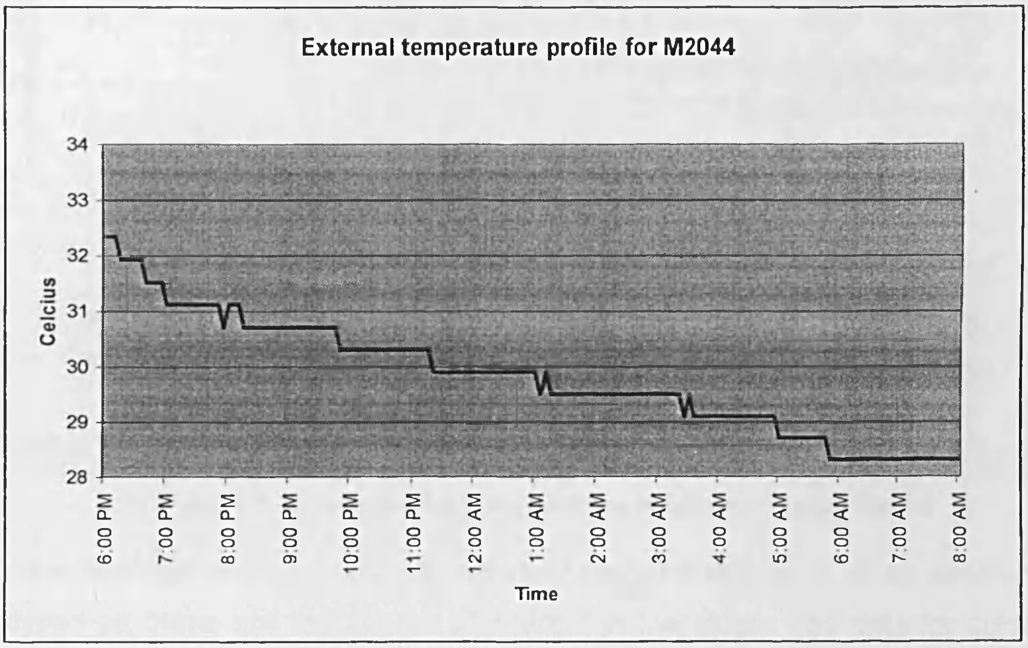

Figure 8-1 A typical external temperature profile during monitoring period

8.2.2 Indoor air temperature

Figure 8-2 below shows the variation in air temperature between the periods 6 pm to 8am the next morning. For clarity, only the profiles of a few selected cases were plotted to show the extent of variations between cases. Detailed analysis of the variations is conducted in section 8.2.6.

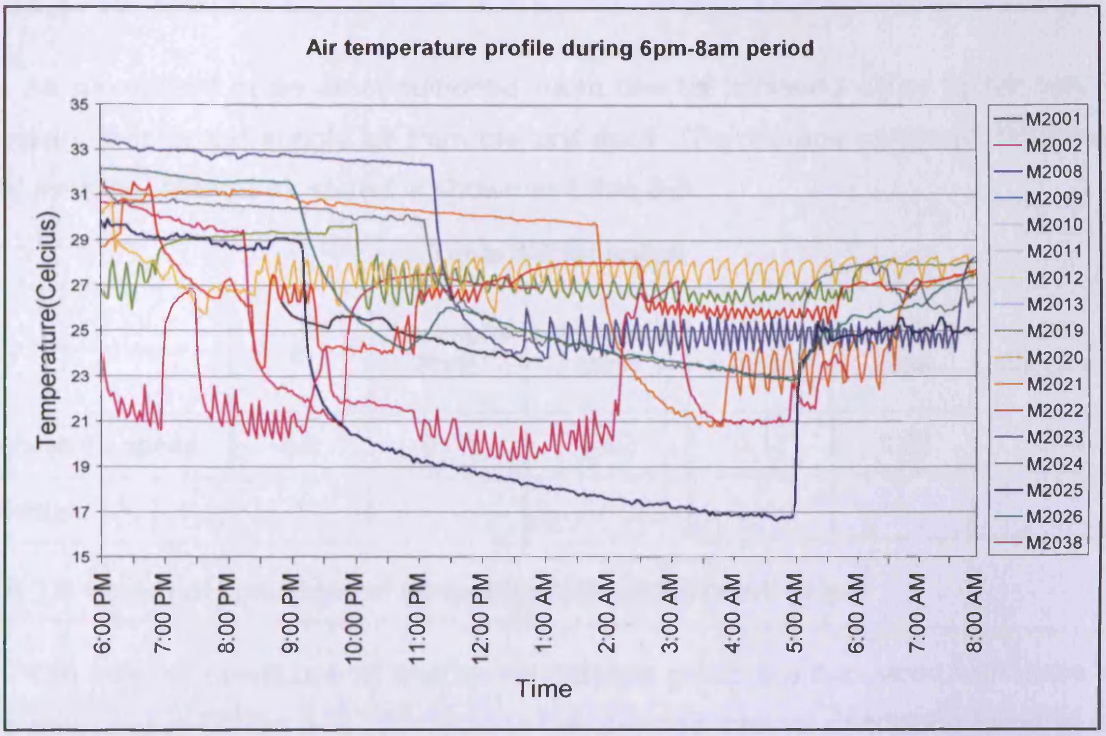

Figure 8-2 : Indoor Air temperature profiles of some cases

The average internal air temperature during the operation of air-conditioners is analysed as these are the values of interest in the study. The data for coldest and warmest case are also identified. The result is shown in Table 8-3.

Table 8-3: Average Indoor Air temperature during operation of air-conditioner

	N	Coldest case (°C)	Warmest case (°C)	Mean (°C)	Std. Error	Std. Deviation
Average Air temperature	29	18.2	29.1	24.1	0.5	2.7

8.2.3 Relative humidity

The use of air-conditioning also has the effect of removing moisture content in the air-conditioned space. The average internal relative humidity (minimum and average) during AC use is shown in Table 8-4 below.

Table 8-4: Relative humidity

	N	Minimum (%)	Maximum (%)	Mean (%)	Std. Error	Std. Deviation
Average Relative humidity	29	44.8	86.4	56.3	1.69	9.1

8.2.4 Air speed

Air movement in an air-conditioned room can be achieved either by the use of auxiliary fans or the supply air from the unit itself. The average minimum, maximum and average internal air speed is shown in Table 8-5.

Table 8-5 Air speed

	N	Minimum (m/s)	Maximum (m/s)	Mean (m/s)	Std. Error	Std. Deviation
Average Air speed	28	0.00	0.62	0.13	0.02	0.10
Missing	1					

8.2.5 Internal conditions of control (non air conditioned) group.

The internal conditions of non air-conditioned group are compared with those of the main group (Table 8-6). Comparing the average internal conditions found in air conditioned cases (24.1°C) and non air condition cases (30.3°C) reveals an average reduction of 6.2°C when air-conditioning was in use. The difference in average relative humidity between the air-conditioned cases (56.3%) and non air-conditioned cases (70.7%) is 14.4%. The air speed in air conditioned rooms is found to be 0.18m/s slower than the control group.

Table 8-6: Comparison of internal conditions

	Group	N	Minimum	Maximum	Mean	Std. Deviation
Air temperature (°C) p=0.000*	AC	29	18.2	29.1	24.1	2.7
	Non AC	9	29.3	31.0	30.3	0.5
Relative humidity (%) p=0.000*	AC	29	44.8	86.4	56.3	9.1
	Non AC	9	61.5	79.3	70.7	5.8
Air speed (m/s) p=0.005*	AC	28	0.00	0.62	0.13	0.10
	Non AC	9	.02	.63	.31	0.2

*The difference seen is significant to 99% level

8.2.6 Thermal variations (thermal profile)

Following the monitoring study, it was observed that the variation of temperature fell naturally into two types of profile. The first showed that stabilisation had occurred during the night. While the second showed that the temperature continued to fall until the unit was switched off in the morning. An example of a stabilised profile is shown in Figure 8-3

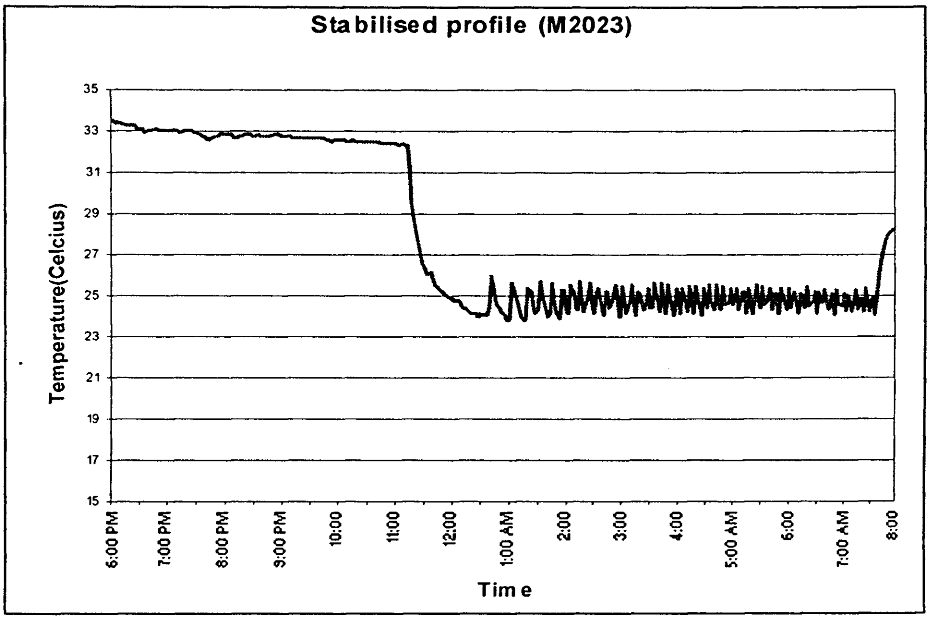

Figure 8-3: Example of stabilised profile (case no M2023)

Stabilisation is identified by a profile where there are small fluctuations about a temperature along a generally horizontal line. This pattern is the result of thermostatic switching on and off, regulating the internal condition around a selected temperature. In this particular case the temperature setting used was 26°C. In the figure, it can be seen that the unit was switched on around 2300, hence the sharp drop. It then cools down to 24°C at around 0030 and stabilized between 24°C and 26°C.

An example of non-stabilised profile is shown in Figure 8-4 below. In this case, the unit was switched on at 9pm and the cooling took place from 2100 to 0500. The temperature setting in this case was 16°C. Although the rate of cooling changes, the temperature never stabilised, reaching as low as 17°C at 0500 when the unit was switched off.

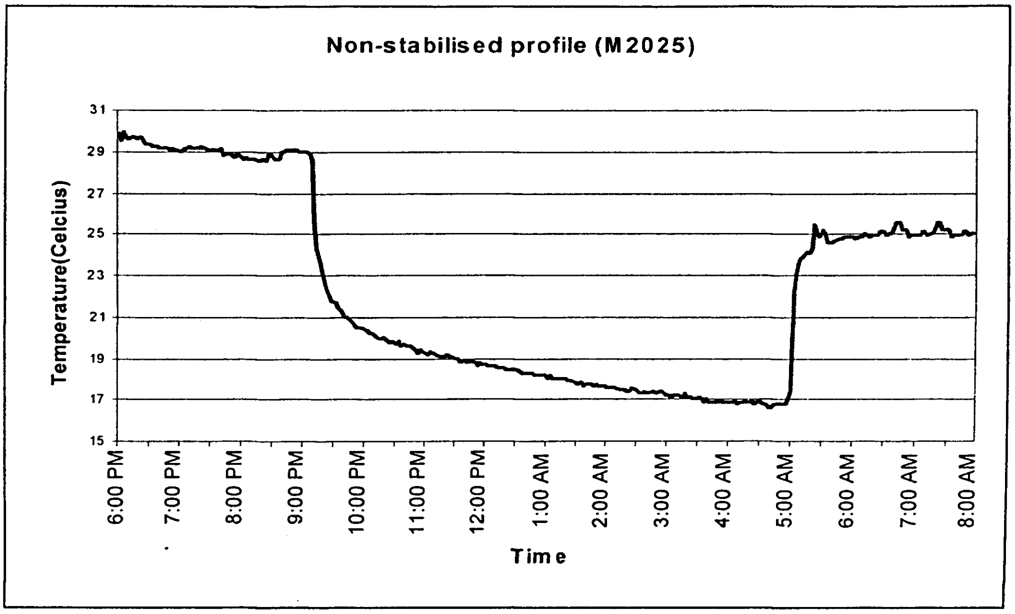

Figure 8-4: Non stabilised profile (Case no 2025)

The reason for this difference in profile is interesting and worth investigating. Investigation of room size reveals that M2023 in fact has larger room volume ($1500m^3$) compared to M2025 ($1200m^3$). Both cases use units of similar power (1hp). The reason for the difference could be due to the lower temperature setting used in M2025. Table 8-7 shows the distribution of the two profile types identified in the survey.

Table 8-7: thermal profile types

	Frequency	%
stabilised	18	62
non stabilised	11	38
Total	29	100.0

8.2.7 Cooling Characteristics

The temperature profile when air-conditioning is being used is further divided into two phases: cooling, and stabilisation. The cooling phase is used to identify the rate of reduction of temperature over time. Stabilised phase is the duration when the thermal condition is stabilised. For illustration, case M2023 is discussed here. The two phases are illustrated in Figure 8-5 below. There's no stabilisation phase in non-stabilised cases.

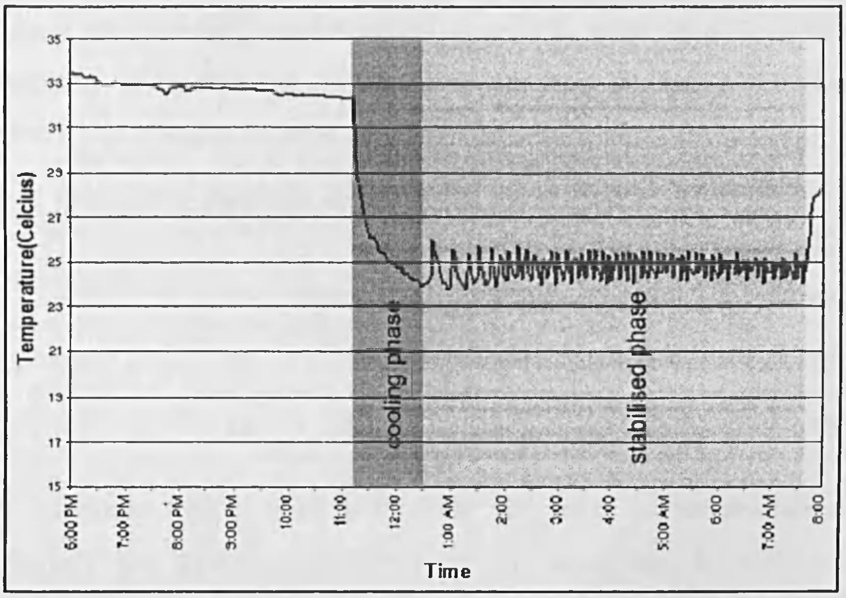

Figure 8-5 Description of cooling phase and stabilised phase (case M2023)

A stabilised temperature profile indicates that the internal condition has probably reached the set temperature and the thermostatic function of the units is being employed. (In this particular case, the temperature was set at 26°C). A non stabilised profile poses a possible problem to the comfort of occupants. Since cooling takes place over a longer period, it is possible that the internal condition cools down below the lower comfort boundary during sleeping hours, and hence necessitates remedial action by interrupting their sleep. The adjustment operation and other behavioural issues are discussed in the next section.

The analysis of the cooling and stabilisation phase for all 29 cases is shown in Table 8-8. From the table, it is found that, on average, during cooling period, the air temperature drops as much as 3°C every hour, within an average duration of cooling phase of 207 minutes (3 hours 27 minutes). The average air temperature reduction during cooling is 5°C.

Table 8-8: Average cooling characteristics of all cases

	N	Minimum	Maximum	Mean	Std. Deviation
Cooling temperature difference (°C)	29	1.4	9.9	5.0	2.4
Cooling duration (min)	29	12	713	207	196.9
Cooling gradient(°C/hour)	29	0	10.2	3.0	2.4

There are 18 cases where stabilised profiles were achieved. The result is shown in Table 8-9 below. On average, stabilisation occurs around 25.4°C, with average duration of stabilised temperatures being 300 minutes (5 hours). However the standard deviation for this value is large (146 minutes= 2 hours 26 minutes).

Table 8-9: Average stabilisation characteristics

	N	Minimum	Maximum	Mean	Std. Deviation
Stabilised temperature (°C)	18	20.4	29.3	25.4	2.8
Stabilised duration (min)	18	95	545	303.9	146.2

This finding suggests that a steady thermal condition is not always achieved when air-conditioners are operated. Even it is are achieved, it might not occur throughout the whole sleeping duration, and the durations that occur differ widely between cases.

The reason for non stabilised profiles cannot be determined from the data gathered. However it may be attributed to the inadequacy of unit's power rating to cool the intended space. This results in the internal conditions not achieving the set temperature immediately, but rather follows the movement of external air temperature as the cooling efficiency improves with the gradual lowering of external conditions. Even if the power rating suffices under normal condition, high infiltration rate by extensive openings of doors and windows which brings in more heat and humidity may also cause a similar situation.

8.3 Adaptive Behaviour

This section discusses the findings of behavioural investigation of the study. The adaptive behaviours analysed in the study are:

1. Operations of air-conditioning units
2. Operation of auxiliary fans (if any)
3. Use of covers: Thickness of blanket

The operations of air-conditioners by occupants reveal the use pattern of this appliance at home. As had been discussed in previous chapters, the use pattern has a significant impact on the energy demand from air-conditioning use.

The use of auxiliary fans is also examined. As had been discussed, without air-conditioning, cooling by forced convection is the major strategy in achieving comfort in Malaysian homes. Introduction of air movement has the effect of raising the comfort temperature. As such, it is necessary to identify the use of auxiliary fans in each case. Subsequently, analysis of the difference in comfort temperatures between the cases using auxiliary fans and the cases which did not is conducted in the discussion.

The insulation level of covers used by occupants is examined as this is one of the six major factors affecting thermal comfort. Apart from the clothing value, the use of covers is also analysed.

8.3.1 Operations of air-conditioning units

In the survey, occupants were asked to record their actions in operating the air-conditioning units. Items of investigation are, duration of operation, time of operation and temperature setting. The objective of this analysis is to establish the use pattern of air-conditioning units.

8.3.1.1 Duration of operation

Table 8-10 below shows the duration of use of AC units, differentiating between weekends and weekdays use in hours.

Table 8-10: Duration of operation of units

Weekdays or weekend	Mean (hours)	N	Std. Deviation (hours)
weekdays	6.6	16	3.1
weekends	7.5	12	3.0
Total	7.0	28	3.0

$p=0.48$, $p>0.05$

The t-test analysis showed that although there is a difference between the average duration of use between weekdays (6.6 hours) and weekends, the difference is not large and not significant ($p=0.48$). This can possibly be explained by the fact that in both cases, the units are mostly used during the night, eliminating the difference due to daytime working hour during weekdays.

8.3.1.2 Time of operation

Table 8-11 shows the time when the units were switched on and the time they were switched off. For the purpose of analysis, the hour 6pm, when the monitoring started was assigned the value zero hour. From the table, it can be seen that the time the AC unit is switched on is, on average on the 4.1th hour, i.e. around 10.05 pm and switched off on 11.6th hour, i.e. around 5.35 am.

Table 8-11: Time of operation (hour)

	N	Earliest	Latest	Mean	Std. Deviation
Time AC switched on	29	0.00	8.2	4.1	2.3
TIme AC switched off	26	7.00	15.8	11.6	2.1

The time of operation for all cases is shown in Table 8-12. It can be seen from the table that the time when almost all the cases had their units in operation was the time between midnight and 2 am.

Table 8-12: Time of operation of units during monitoring period (marked with shaded cells)

Case no.	Hour (time)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM
M2001														
M2002														
M2003														
M2004														
M2005														
M2006														
M2007														
M2014														
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M2019														
M2021														
M2022														
M2023														
M2024														
M2025														
M2026														
M2028														
M2029														
M2030														

	Hour (time)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	7:00 PM	8:00 PM	9:00 PM	10:00 PM	11:00 PM	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM
M2031														
M2032														
M2033														
M2035														
M2037														
M2039														
M2041														
M2043														

8.3.1.3 Conditions of operations

The internal conditions when the air-conditioning units were switched on and switched off were examined. Table 8-13 shows the internal temperatures when air-conditioning units were switched on. On average, the units were switched on when the temperature was 29.4°C.

Table 8-13 Internal temperatures when units were switched on

	N	Minimum	Maximum	Mean	Std. Deviation
Temperature when AC is switched on (C)	25	26.1	32.6	29.4	1.89

Table 8-14 shows the internal temperatures when the units were switched off. On average, the units were switched off when the temperature was 24.0°C.

Table 8-14 Internal temperatures when units were switched off

	N	Minimum	Maximum	Mean	Std. Deviation
Temperature when AC is switched off (C)	26	17.3	29.2	24.0	2.95

8.3.1.4 Temperature settings

The temperature settings used by occupants is analysed. For every case, the temperature settings used at the start of operation and in the subsequent adjustments were recorded. The results are shown in Table 8-15 below and illustrated in Figure 8-6

Table 8-15: Temperature settings

	N	Minimum	Maximum	Mean	Std. Deviation
Start temp setting (°C)	29	15	29	21.2	3.9
1st adjusted temp (°C)	13	17	27	22.0	3.2
2nd Adjusted temp (°C)	7	21	27	25.0	2.0
3rd adjusted temp (°C)	2	24	28	26.0	2.8

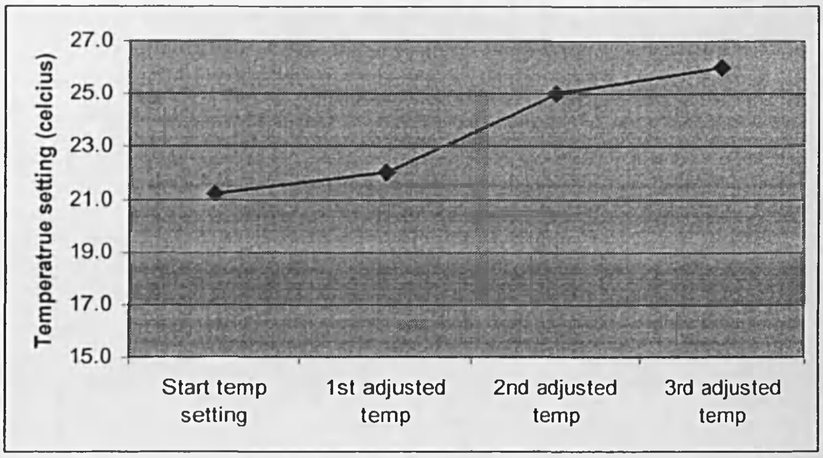

Figure 8-6 Average Temperature setting chosen by occupants

The average setting used by occupants when the units were switched on was 21.2°C. It can be seen that the subsequent adjustment has increasing average temperature setting following the number of adjustments done. It can be concluded from this finding that adjustments to the units were carried out due to cold sensations experienced, hence the need to adjust to higher settings.

8.3.1.5 Adjustment types

From the data, it became clear that there are two types of adjustment done to the units during the occupancy period. The first is mid sleep adjustment, where the adjustment is carried out during normal sleeping hours, i.e. user wakes up to adjust the unit and then go back to sleep. Post sleep adjustment indicates adjustments of the unit (includes switching off) when subjects woke up for the day. The result is shown in Table 8-16 below.

Table 8-16: Adjustment type

	Frequency	Percent (%)
Mid sleep adjustment	13	45
Post sleep adjustment	16	55
Total	29	100.0

The results show a high number of cases (45%) where occupants interrupt their sleep in order to adjust the setting of the AC unit. This problem is commented on further in the discussion section.

8.3.1.6 Use of timer

The use of a timer in each case is investigated. The use of timers for switching on and switching off are shown in the Table 8-17 below.

Table 8-17: Use of timer

	Turning on		Turning off	
	Frequency	Percent (%)	Frequency	Percent (%)
no	28	97	23	79
yes	1	3	6	21
Total	29	100.0	29	100.0

It can be seen that in the majority of the cases investigated, timers were not used for the operation of the units. Only in one case was it found that the timer was being used to start the operation of the unit. The majority of the cases do not use the timer for switching off the units (23 cases=78%).

8.3.2 Use of auxiliary fans

The use of forced convection by means of an electric fan is investigated. The use is categorised into:

1. No auxiliary fan use: where auxiliary fans were never used during occupancy period.
2. Exclusive use without air-conditioners: where the auxiliary fans were used only when the air-conditioning units were not in operation.
3. Simultaneous use with air-conditioners: where auxiliary fans were used while air-conditioners were in operation.

Table 8-18 below shows the results. From the table it can be seen that 9 cases did not use auxiliary fans at all and nine cases used them exclusively without the air-conditioning units operation. This forms a cumulative percent of 62% of the cases that did not employ the use of forced convection whilst using air-conditioning units. In

11 cases (38%), it was found that auxiliary fans were used simultaneously with air-conditioning units.

Table 8-18: Use of auxiliary fans during Air-conditioning operation

Auxiliary fan use category	Frequency	Percent (%)	Cumulative Percent
Did not use ceiling fan	9	31	31
Use exclusively without AC units	9	31	62
Simultaneous use with AC units	11	38	100
Total	29	100	

Table 8-19 shows the duration of use of these fans found in both cases when they were used (exclusive and simultaneous use). From the table it can be seen that the average operation is 6.7 hours. The maximum duration of operation is 13 hours. The minimum duration of operation is 0.95 hour (57 minutes). However the standard deviation is large (3.45 hours)

Table 8-19: Duration of use of auxiliary fans (hour)

	N	Minimum	Maximum	Mean (hrs)	Std. Deviation
Fan operating duration (hours)	20	0.95	13.0	6.7	3.45

8.3.3 Clothing insulation

Clothing levels are established by occupants selecting list of clothing articles they wore on the schedule given in the survey form (item 4 in Appendix 5). The values were derived from the clothing values specified in ISO 7730. The results are shown in Table 8-20.

Table 8-20 Clothing insulations

Gender	N	Mean	Std. Deviation
Female	23	.31	.14
Male	25	.20	.06
Total	48	.25	.12

$p=0.001$, $p=<0.01$, difference significant to 99% level

The average clothing value for females is found to be 0.11 higher than the males. Even though the difference is statistically significant, the standard deviation is large in both cases.

The clothing value established in this study does not reflect the total insulation levels, since the total insulation level during sleeping has to take into consideration the effect of added insulation by subjects lying on beds and their use of covers. For the purpose of this study, however, the degree of insulation levels are analysed by the thickness of the blankets employed by occupants.

8.3.4 Type and use of blankets

The use of blankets is investigated. In the survey form, respondents were asked the types of blankets they used for sleeping. Although people use their blankets in varying degree and at various times, it is the thickness of blanket would be the determining factor in occupants' comfort sensation, hence the analysis focuses on this variable, categorised into two blanket groups, as had been explained in Chapter 6. Similar information from the control group, with 14 subjects, was also obtained. The results for both cases are shown in Table 8-21 below:

Table 8-21: Blanket type

Normal covering used	Main		Control	
	Frequency	Percent (%)	Frequency	Percent (%)
No covering	2	4	8	57
Normal	32	63	6	43
comforter	16	33	0	0
Total	48	100	14	100.0

It is found that around 33% of the respondents in air-conditioned rooms use a comforter as their covers during sleeping. Comparing the results with those of the control group, it is found that no subject used a comforter. This is in agreement with the findings from the preliminary survey in Chapter 7. In the control group, 8 people were found not using any form of covers during sleeping (57%). This is in contrast with the main group where only 2 were found to be sleeping without covers (4%).

8.4 Discussions of results

The above findings shed some light into the internal conditions and the use pattern of air-conditioners in homes during night time occupancy. The findings can also be used to speculate on the relationship between the internal conditions and the behavioural pattern of occupants in achieving comfort. The following sections discuss these findings in terms of the relationship between the environmental conditions and several parameters gathered in the study.

8.4.1 Unit sizing

Each air conditioning unit is designed to provide optimum cooling for a certain size of space. A correctly sized air-conditioning unit will be able to achieve the set temperature in a room effectively. Since in the survey, most of the units are of the same power rating (i.e. 1hp), it is the size of the room that can possibly determine the ability for a unit to achieve the set temperature.

It is unlikely an occupant will choose a temperature based on the size of a room. A correlation analysis between the volume of the rooms (in cu.ft) and the average internal condition is conducted and the result is shown in Table 8-22 below.

Table 8-22 Correlation analysis between room size and average air temperature

		Average Air temperature (°C)
Volume of conditioned space	Pearson Correlation	.04
	Sig. (2-tailed)	.847*
*p=0.847,p>0.05	N	29

It is found that in the survey, the volume of the room has no significant correlation on the average air temperature monitored during air-conditioning period. (p=0.847, p>0.05). The Pearson correlation is also found to be low (0.04). From the results, it can be concluded that the size of the room does not influence the resulting internal conditions, indicating that on average, the units are adequately sized for the rooms monitored.

8.4.2 Temperature setting and profile types

The ability of the units to achieve stabilised conditions also depends on the temperature setting chosen by occupants. If the set temperature is close to the existing conditions prior to the use of air-conditioners, it will be quicker for the units to achieve the set temperature. Another reason is there might be insufficient power of the units in some cases to achieve the lowest temperature setting. An analysis of the average set temperature between the two profile types is analysed. The result is shown in Table 8-23 below.

Table 8-23: Average temperature settings and profile types

	Profile type	N	Mean (C°)	Std. Deviation	Std. Error Mean
Start temp setting (°C)	stabilised	18	22.5	4.0	.944
	non stabilised	11	19.0	2.6	.780

($p=0.018$, $p<0.05$) The difference is significant to the 95% level

From the result, it can be argued that choosing a higher temperature setting increase the likelihood of achieving stabilised condition.

8.5 Influence of behavioural pattern on internal conditions.

Analysis of internal conditions reveals large variations in average conditions between the coldest case and the warmest case (almost 10°C difference in average internal air temperature, and almost 12°C difference in minimum temperature). This large variation in the average internal conditions chosen by occupants can be attributed to personal variations in clothing levels and covering insulation levels, as well as the employment of auxiliary fans, which allows higher temperature for comfort. It can thus be argued that the occupants' behavioural pattern has a strong influence on the energy consumption of air-conditioning used in homes.

8.5.1 Air temperature and the use of auxiliary fans

The use of forced convection in air-conditioned spaces can save energy by higher temperature setting [2, 3]. The use of auxiliary fans (ceiling fan, table fan etc) in the study is investigated. Distinction is being made between cases using auxiliary fans simultaneously and cases which did not. The average air temperatures of the two groups are now examined. As shown in Table 8-24 below, the difference is 3.3°C and is found to be statistically significant ($p=0.00$) (equal variance assumed)

Table 8-24 Use of Auxiliary fans and average air temperature

	Use auxiliary fan simultaneously	N	Mean (°C)	Std. Deviation	Std. Error Mean
Average Air temperature	no	17	22.8	2.4	.5843
	yes	12	26.1	1.6	.4709

The difference is significant to the 0.01 level ($p=0.00$, $p<0.01$)

From the result it can be seen that the use of an auxiliary fan correlates with higher average air temperature. Two interpretations can be developed from this finding. First, with higher air speed (by the use of auxiliary fans), people will choose higher temperature due to the extra cooling effect of forced ventilation. A second possibility is by the use of auxiliary fan, cool air from the unit is distributed more uniformly in the room, and as a result, higher temperature settings can be comfortable for occupants.

8.5.2 Type of blankets and air temperature

The act of putting on a thicker cover has the effect of increasing the overall thermal vote of a subject, whereas in using AC, the energy is used to reduce the thermal vote. This conflicting movement of thermal direction indicates energy waste. In this section the relationships between cover levels and other parameters are examined.

The average air temperature and the use of comforters are investigated. The table below shows the average temperature between cases where all the occupants used comforter (22.1°C) and cases that did not (24.9°C). T-test results shows that the difference is significant ($p=0.008$) (Table 8-25).

Table 8-25 Blanket type and average air temperature for cases when both occupants use comforters.

P=0.008	Households with both occupants use comforters	N	Mean (°C)	Std. Deviation	Std. Error Mean
Average Air temperature	yes	8	22.1	3.0	1.05
	no	21	24.9	2.1	.46

P=0.008., $p<0.01$ The difference seen is significant at the 99% level

The result suggests that comforters are used in conditions where the average internal temperatures are colder. Since in an air conditioned rooms, the internal condition is regulated by the operation of air-conditioner, it can thus be argued that the use of comforters results in occupants operate their units to colder conditions.

8.5.3 Use of timer and adjustment types

A high percentage of cases were found where the adjustments were made during normal sleeping hours, as much as 45%. This indicates there is room for improvement in air-conditioner design to avoid sleep disturbances. The use of timers, which probably would reduce sleep disturbance, is very low, with only 21% of the cases where timer was used for switching off (see Table 8-17).

Table 8-26 shows the cross tabulation analysis between the use of timers and the need for adjustment during sleeping hours. It reveals a lower percentage of mid-sleep adjustments if timers are used for switching off (33%) compared to cases not using timer (52%). What is interesting to note is that even with the use of timer for switching off; there are 33% of these cases where the occupants still need to adjust the units during mid sleep.

Table 8-26 Use of timer and adjustment type

use of timer for switching off units	Adjustment type		Total (%)
	Mid sleep adjustment	Post sleep adjustment	
no	12 (52%)	11(48%)	23 (100%)
yes	2(33%)	4(67%)	6 (100%)
Total	14	15	29

8.6 Summary

The analysis of environmental conditions and occupants behaviour in the main field survey reveals several important issues in the use of air-conditioning during night time occupancy. The relationship between units' characteristics and occupants' behaviour and the internal conditions are established.

On average, the units were turned on when the internal temperature was 29.4°C and turned off when it reached to 24.0°C. Investigation of the thermal profile reveals that a significant number of cases were found to have failed to achieve stabilised internal conditions during the use of the air-conditioning (38%). The internal conditions kept getting cooler until the units were switched off.

The time it takes for the cooling of the internal conditions in stabilised cases is also relatively long. As a result, it is possible that the internal conditions got colder than the lower comfort boundary during sleeping hours. This is illustrated by a number of cases where occupants had to wake up during sleeping hours to carry out adjustment to the unit's settings (45%). Analysis of subsequent adjustments to the temperature settings shows that they are done in response to cold sensations.

The use of comforters in 33% of the cases reveals the possibility of overcooling in some cases, since this type of cover was not used in non-air-conditioned cases and the majority of the air-conditioned cases. This can reasonably be argued as the case as the average temperature found in cases where comforters were used by both occupants was 2.8°C cooler than the average found in other air-conditioned cases.

A better control strategy is needed to provide a better comfort experience for users. Even in cases where timers are being used for switching off the units, around 33% of these are cases are where people have to interrupt their sleep to carry out adjustment to the units' operation.

8.7 References

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9 Results of field survey: Thermal comfort analysis

9.0 *Introduction*

The main objective of the thermal comfort study is to establish the range of temperatures within which people find themselves comfortable. This information is valuable for the provision of comfort conditions, especially when energy is needed in cooling or heating. Energy efficiency and optimum comfort for occupants will be the outcome made possible by such information. In the adaptive approach to thermal comfort, it is accepted that this range varies between different populations depending on various factors such as climate and geographical locations. This study aims to establish the thermal neutralities and the comfort range for air-conditioned rooms during night time occupancy in Malaysia.

The methodology adopted for the current study is the field survey approach. Environmental parameters are monitored 'in-the-field' and corresponding subjective personal evaluations by subjects are recorded by the votes they cast on the ASHRAE seven point sensation scale [1]. This chapter presents the thermal comfort analysis of the study and the results are compared with other findings from the region. The method of analysis for this chapter has been discussed in Chapter 6. The findings are also compared with the adaptive models discussed in the literature review.

The values for thermal neutrality and the range of comfort conditions established form the study are then used to establish general comfort criteria for occupancy in air-conditioned bedrooms during night time occupancy. The thermal conditions of the air conditioned rooms found in this study can then be evaluated in terms of meeting these criteria.

9.1 *Description of subjects and sample votes*

In the study, 48 subjects cast their votes at various points during the monitoring period. A total of 136 votes were cast. This section analyse the characteristics of these votes. In conducting further analysis, distinction has to be made between votes cast at various metabolic rates and blanket types and uses.

9.1.1 Subject distributions

For the 29 households monitored, each room monitored had at least one subject sleeping in the room and filling in the survey form. Nineteen of the households had two subjects participating in the monitoring. A total of 48 subjects cast their votes in the survey. Out of this, 23 are female and 25 are male. The mean age of the population is 33.4 years old (Table 9-1)

Table 9-1 Age, gender and vote distribution of air-conditioned population

Gender	Frequency	Mean Age (yrs)	Std. Deviation	Number of votes
female	23	32.8	7.2	66
male	25	34.0	8.4	70
Total	48	33.4	7.7	136

9.1.2 Vote distribution

A total of 136 votes were cast from the 48 subjects monitored in the survey. For each vote the corresponding personal parameters are readily available from the survey forms, e.g. time of vote and blanket thickness. The corresponding environmental parameters are identified by matching the time of the votes and the time the environmental variables are recorded by the data logger.

Even though some subjects cast more than two votes (especially those who woke up mid sleep), each of the votes are treated as a single data in the analysis. The possibility of subjects' personal bias is considered insignificant for the analysis. The assumption made is that the subjects are homogenous in terms of metabolic rate (sleeping), occupancy type (residential) and have similar psychological expectation (comfort in air conditioned room). The differences investigated are thus thermal conditions (temperature and humidity) and blanket type, which differs between each vote.

For the purpose of analysis, it is necessary to classify the votes into categories that might have different personal parameters that affect their assessment of the thermal conditions. The personal parameters investigated in this study are the metabolic rate and the thickness of blanket used by the subjects.

The difference in metabolic rate between going to bed and actually sleeping needs to be established. Every subject was asked to cast at least two votes. The first vote was cast at the time when the subject went to bed. The metabolic rate assumed for this vote is that of a sedentary person, i.e. met 1.0. The next vote was cast at the time the subject woke up in the morning, in which case the metabolic rate is assumed as 0.7 (for a sleeping person). They were also asked to cast votes anytime and as soon as they woke up during the night. Any vote cast if the subject happened to wake up in the middle of the night is also assumed to be that of a sleeping person (0.7 met). Table 9-2 below shows the distribution of the votes between the two metabolic rates.

Table 9-2 metabolic rate distributions

	Frequency	Percent (%)
Going to bed (met 1.0)	49	36.0
mid-sleep and waking up (met 0.7)	87	64.0
Total	136	100.0

Another aspect which has direct influence on the value of the votes is the insulation levels. While the information on personal articles of clothing was gathered in the study, only the difference in the blanket thickness employed by each subject is being analysed. Apart from positive correlation already established by the steady state model, personal clothing analysis provides no practical purpose for the objective of this study. The final insulation value for each subject in the study is determined more by the use of covers. As such the focus on the effect of blanket type analysis can provide practical comparisons between two groups identified earlier, i.e. normal blanket and comforter type blanket. The impact of social and cultural phenomena of employing comforter type blanket for air-conditioned spaces can then be investigated. The distribution of blanket use by subjects when casting the votes is shown in Table 9-3. Votes cast when subjects did not put on any covers are also identified.

Table 9-3: Blanket type

Blanket type	Frequency	Percent (%)
No blanket	27	19.8%
normal	69	50.7%
comforter	40	29.4%
Total	136	100.0%

9.2 *Correlation with environmental variables*

The correlation between thermal sensation votes (Tsv) and the environmental variables are examined. For this analysis, all votes (136) are used. The result is shown in Table 9-4. It is found that, with the exception of air speed, there is a significant correlation between the thermal sensation votes and all the other parameters. Air temperature, globe temperature, mean radiant temperature and operative temperature have significant correlations at the 0.01 level (99% confidence interval) while relative humidity has significant correlation at the 0.05 level (95% confidence interval).

Table 9-4 Correlations between Tsv and environmental parameters

Thermal sensation vote		Air temperature (C°)	Globe temperature (C°)	Relative humidity (%)	Mean radiant temperature (C°)	Operative temperature (C°)	Air speed (m/s)
	Pearson Correlation	.492(**)	.486(**)	.189(*)	.452(**)	.492(**)	.021
	Sig. (2-tailed)	.000	.000	.028	.000	.000	.821
	N	136	136	136	136	136	123

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

While air speed is an important factor in determining comfort sensation, the weakness of the correlation between the air speed variables in this study can be attributed to several factors. First it has been established from the behavioural analysis in chapter 8 and in the preliminary survey in Chapter 7 that even though the units fan operates to distribute cold air in air-conditioned bedrooms, forced convection over subject's body is not widely employed as a cooling strategy. Secondly, for a forced convective cooling to be effective in warm condition, it needs to be in the range of 0.5m/s to 1.0m/s [2], whereas the air speed measured near the subjects in the present study averages only 0.02m/s. Another possible explanation is the fact that in the study, measurement of air speed cannot be taken at the exact location where subjects were sleeping. In thermal comfort study, air movement over the skin of subject is important as it affects their thermal perception. As such the actual air movement experienced by subjects in the study could not be measured accurately for thermal comfort analysis.

9.3 *Average thermal sensation and humidity sensation*

A rough evaluation of the condition for the whole sample population can be carried out by taking the average value of all the votes cast in the study. The same is carried out for the humidity sensation. For this analysis, only votes cast at a metabolic rate of 0.7 (sleep) is used (i.e. 87 votes)

9.3.1 Average thermal sensation vote and average humidity vote

The maximum, minimum and average values of the thermal votes acquired in this study are shown in Table 9-5 below. Thermal sensation votes are cast on a 7-point ASHRAE scale. (-3=cold, 3=hot). The mean thermal sensation vote for the whole sample is found to be - 1.16. This value is lower than the minimum value for acceptable general comfort class B as specified in ASHRAE Standards 55 [3] for 90% acceptability which states that the acceptable condition lies between -0.5 and +0.5. However, this value is within the range of acceptability proposed by the adaptive model in de Dear in ASHRAE RP-884 [4] (i.e. between -1.5 to +1.5).

Responses to humidity sensation are measured by subjects indicating their humidity sensations on a 5-points scale. (-2= Humid, -1=slightly humid, 0=ok, 1=slightly dry, 2=humid). Analyses of the humidity sensation reveal an overall vote of 0.24, indicating sensation on the dry side.

Table 9-5: Statistical summary of votes (met 0.7)

	N	Minimum	Maximum	Mean	Std. Deviation
thermal sensation vote	87	-3	1	-1.16	.926
humidity vote	87	-1	1	.24	.457

Another measure of thermal comfort acceptability generally used in field study is that any vote within the three central values (-1=slightly cool, 0=ok, 1= slightly warm), is acceptable [4]. These values actually correspond to the comfortable range as used in the Bedford scale [5]. Table 9-6 shows the distribution of votes during sleeping hours gathered in the study. It is found that a cumulative of 39.1% of the votes indicate a non-acceptable condition.

Table 9-6 Frequency of votes (met 0.7)

Scale	ASHRAE Thermal sensation votes	Frequency	Percent (%)	Cumulative Percent (%)
-3	Cold	5	5.7	5.7
-2	Cool	29	33.3	39.1
-1	Slightly cool	29	33.3	72.4
0	Neutral	23	26.4	98.9
1	Slightly warm	1	1.1	100.0
2	Warm	0	0	0
3	Hot	0	0	0
	Total	87	100.0	

9.4 *Griffiths Method*

In this analysis, the method adopted by Griffith [8], and revised by de Dear and Brager [9] explained in Chapter 3, is used to establish the neutral temperature for the sample population. In this method, applying Griffiths method on RP-884 database, de Dear and Brager proposed that the increase in temperature for each scale point on the comfort scale was 2K for each point on a 7-point comfort scale [6]. The equation for this relationship is thus:

$$T_n = T_a - (T_{sv})2$$

Equation 9-1

Where T_n is the neutral temperature, T_a is the air temperature when the vote was cast and T_{sv} is the actual votes cast by subjects.

Since the internal conditions do not vary greatly between individual households (standard deviation 2.7°C for average temperature-see Chapter 8), it can be argued that the difference in personal thermal variables between individuals is more significant than the difference between households. As such it is more appropriate to categorise votes into different blanket categories than into different household units. Hence, the unit of analysis employed in this study is the individual votes as opposed to household means as proposed by de Dear [4].

The neutral temperature for each vote established by using this method is shown in Table 9-7. The mean neutral temperature of the votes is calculated, and the result is shown in Table 9-8.

Table 9-7 Neutral temperatures for all votes (Griffiths revised method)

No.	Blanket type	*A* Thermal sensation votes	*B* Air temperature (C°)	*C* Operative temperature (C°)	*B-2(A)* Neutral air temperature (C°)	*C-2(A)* Neutral operative temperature (C°)
1	comforter	-2	24.1	25.8	28.1	29.8
2	comforter	-2	23.7	27.6	27.7	31.6
3	comforter	-2	23.4	22.3	27.4	26.3
4	comforter	-2	23.7	20.9	27.7	24.9
5	comforter	-2	23.4	20.0	27.4	24.0
6	normal	-2	26.0	26.8	30.0	30.8
7	normal	-1	27.5	24.7	29.5	26.7
8	normal	-1	20.7	25.5	22.7	27.5
9	normal	-1	19.0	25.7	21.0	27.7
10	normal	-3	18.6	26.5	24.6	32.5
11	normal	-2	25.8	26.8	29.8	30.8
12	normal	-1	23.5	24.9	25.5	26.9
13	normal	0	24.6	23.3	24.6	23.3
14	normal	-3	25.4	25.6	31.4	31.6
15	normal	0	26.1	25.2	26.1	25.2
16	normal	0	26.6	25.6	26.6	25.6
17	comforter	-1	25.4	25.2	27.4	27.2
18	comforter	-1	26.1	25.4	28.1	27.4
19	comforter	0	26.6	25.2	26.6	25.2
20	normal	-1	24.1	25.2	26.1	27.2
21	normal	-2	22.5	29.1	26.5	33.1
22	normal	-2	24.8	30	28.8	34.0
23	normal	-2	24.5	27.3	28.5	31.3
24	normal	-2	24.8	28.2	28.8	32.2
25	normal	-3	24.5	27.3	30.5	33.3
26	comforter	0	20.6	27.1	20.6	27.1
27	comforter	0	18.5	28.3	18.5	28.3
28	comforter	-1	20.0	25.0	22.0	27.0
29	comforter	-1	20.6	26.7	22.6	28.7
30	normal	-1	24.8	28.2	26.8	30.2
31	normal	-1	24.8	26.2	26.8	28.2
32	normal	-1	24.8	25	26.8	27.0
33	normal	0	28.7	26.1	28.7	26.1
34	normal	-1	29.7	25.9	31.7	27.9
35	normal	0	26.6	25.6	26.6	25.6
36	normal	0	27.9	25.9	27.9	25.9
37	normal	0	26.7	25.8	26.7	25.8
38	normal	-2	26.6	25.6	30.6	29.6
39	normal	0	28.1	24.8	28.1	24.8
40	normal	-1	24.2	24.4	26.2	26.4
41	normal	-2	26.7	24.2	30.7	28.2
42	normal	1	28.0	26.4	26.0	24.4
43	normal	-1	25.8	23.7	27.8	25.7
44	normal	-2	24.1	25.1	28.1	29.1
45	normal	-1	25.7	29.4	27.7	31.4
46	normal	0	24.1	29.4	24.1	29.4

No.	Blanket type	*A* Thermal sensation votes	*B* Air temperature (C°)	*C* Operative temperature (C°)	*B-2(A)* Neutral air temperature (C°)	*C-2(A)* Neutral operative temperature (C°)
47	normal	0	24.7	27.2	24.7	27.2
48	normal	0	24.7	28.2	24.7	28.2
49	normal	0	24.8	27.2	24.8	27.2
50	normal	-1	24.1	28.2	26.1	30.2
51	normal	-2	23.3	21.1	27.3	25.1
52	normal	-2	23	23.8	27.0	27.8
53	comforter	-2	17.3	27.1	21.3	31.1
54	comforter	-2	18.0	24.3	22.0	28.3
55	normal	-2	23.3	29.2	27.3	33.2
56	normal	-3	25.9	28.6	31.9	34.6
57	normal	-2	22.9	30.5	26.9	34.5
58	normal	-1	24.1	30.8	26.1	32.8
59	normal	0	29.4	24.7	29.4	24.7
60	normal	0	29.4	24.3	29.4	24.3
61	No blanket	-1	26.5	23.9	28.5	25.9
62	No blanket	-2	28.0	24.3	32.0	28.3
63	normal	-1	26.5	24	28.5	26.0
64	normal	-2	28.0	25.7	32.0	29.7
65	comforter	-1	20.0	26.5	22.0	28.5
66	comforter	-1	19.0	26.8	21.0	28.8
67	comforter	-1	27.7	22.0	29.7	24.0
68	comforter	-1	27.7	19.7	29.7	21.7
69	No blanket	0	19.7	20.9	19.7	20.9
70	normal	-2	22.5	21.4	26.5	25.4
71	normal	0	27.1	17.9	27.1	17.9
72	normal	-2	23.9	17.7	27.9	21.7
73	normal	-1	28.9	21.4	30.9	23.4
74	normal	0	28.2	20.3	28.2	20.3
75	comforter	-1	28.5	27.9	30.5	29.9
76	comforter	-1	18.4	27.9	20.4	29.9
77	comforter	-1	19.6	28.7	21.6	30.7
78	comforter	-3	18.4	20.0	24.4	26.0
79	comforter	-2	19.9	21.0	23.9	25.0
80	comforter	-1	25.3	20.0	27.3	22.0
81	comforter	0	28.4	21.0	28.4	21.0
82	No blanket	0	30.3	25.8	30.3	25.8
83	No blanket	0	30.6	28.5	30.6	28.5
84	comforter	-2	22.0	25.8	26.0	29.8
85	comforter	-2	22.0	25.4	26.0	29.4
86	comforter	-2	22.0	25.7	26.0	29.7
87	comforter	-2	22.0	25.4	26.0	29.4

Table 9-8 Neutral Temperatures of whole sample of air-conditioned population (met 0.7)

	N	Minimum (C°)	Maximum (C°)	Mean (C°)	Std. Deviation (C°)
Air temperature	87	18.5	32.0	26.8	3.0
Operative temperature	87	19.7	32.4	27.6	2.8

It is found that the neutral air temperature for the sample population is 26.8°C and the neutral operative temperature is 27.6°C.

9.4.1 Average neutral temperature for different blanket groups

For blanket type analysis, it is necessary to exclude votes cast by subjects when they were not employing any blanket (at met rate 0.7). A cross tabulation analysis reveals that there are five votes that fall within this sample (Table 9-9). These votes are therefore excluded, leaving only 82 votes for this analysis.

Table 9-9 Blanket use and blanket type tabulation

		Blanket use		Total
		no	yes	
Blanket type	normal	5	53	58
	comforter	0	29	29
Total		5	82	87

The mean neutral temperatures for the two different blanket groups are obtained from the sample and the difference between them is investigated by conducting an independent sample T-test. The results are shown in Table 9-10.

Table 9-10 Average neutral temperatures between different blanket groups

	Blanket type	N	Mean (C°)	Std. Deviation (C°)	Std error	T-test
Air temperature	normal	53	27.5	2.3	0.3	P=0.000* p<0.01
	comforter	29	25.2	3.3	0.6	
Operative temperature	normal	53	28.2	2.0	0.3	p=0.002* p<0.01
	comforter	29	26.3	3.3	0.6	

*The difference is found significant to 99% level

It is found that the neutral air temperature is 27.5°C for the normal blanket group and 25.2°C for the comforter group. The neutral operative temperature for the normal blanket group is 28.2°C while it is 26.3°C for the comforter group. The mean difference between the two groups achieved a 99% significant level for both air temperature and operative temperature.

9.4.2 Comfort range for air-conditioned bedrooms during night time occupancy.

At the moment there is no established guideline for an acceptable range of comfort conditions in Malaysian homes. The neutral values established in this study are used to produce a range of acceptable conditions for the sample population.

At this point it is necessary to develop criterion of acceptability for the analysis. As discussed in Chapter 2, the definition of acceptability varies between different researchers and establishments. For the purpose of this study, the definition of acceptability by de Dear [10] for the adaptive model is used. Inferring acceptability by proxy from the RP-884 database, he proposed that the range of acceptability should be between the votes of -1.5 to +1.5.

A narrower acceptability range as proposed by ASHRAE Standard 55 [3], is also used for comparative purpose. This standard specifies that for a maximum of 10% PPD, the PMV values should be between -0.5 to+0.5 [11].

The air temperature values derived from the revised Griffiths method are used to establish the lower and upper boundaries of the comfort range for the study. The gradient of a 2K change for every vote change is used to establish the temperature values for the thermal votes of -1.5 and +1.5 (for RP-884) and –0.5 and 0.5 (for ASHRAE 55). The equation for establishing boundary temperature using this method is:

$$T_b = T_n + (T_{sv})2$$

Equation 9-2

Where T_b is the boundary temperature, T_n is the mean neutral temperature and T_{sv} is the thermal sensation vote. To establish the upper and lower boundary values with 10% PPD, T_{sv} is replaced with 0.5, and -0.5 respectively. For acceptability established by the adaptive model, it is replaced with -1.5 and +1.5. The results are shown in Table 9-11.

Table 9-11 Acceptable air temperature range of comfort condition for air-conditioned bedroom during night-time occupancy

Household blanket type group	Neutral air temperature (°C)	Lower Boundary (°C)		Upper Boundary (°C)	
		Tsv=-0.5	Tsv=-1.5	Tsv=+0.5	Tsv=+1.5
normal	27.5	26.5	24.5	28.5	30.5
Comforter	25.2	24.2	22.2	26.2	28.2
Overall	26.8	25.8	23.8	27.8	29.8

The comfort range for night time occupancy of an air-conditioned bedroom can now be established from the values above. For the context of the study, where adaptive opportunities are available, the criterion of acceptability for the adaptive models is more appropriate than the 10% PPD criterion. Hence the comfort range for the normal blanket group is between air temperature of 24.5°C and 30.5°C, while the comfort range for the comforter group is between air temperature 22.2°C and 28.2°C.

9.4.3 Thermal neutrality for non-air-conditioned group.

The dataset for non air-conditioned group is analysed. The distribution of votes in terms of metabolic rate and covering type is shown in the table below:

Table 9-12 Vote distribution (non-air conditioned group)

	Met rate		Blanket type	
	Going to sleep (1.0)	Mid sleep & waking up (0.8)	normal	comforter
No of vote	15	23	38	0
Total	38		38	

In total, 38 votes were cast by the non-air conditioned group. Of these, 23 were cast at met rate of 0.7. All subjects in the non-air-conditioned room used single ply (normal blanket) while sleeping. Using Equation 9-1 on votes cast at met 0.7, the corresponding neutral temperatures are shown in Table 9-13 is shown below. The mean neutral air temperature and operative temperature is shown in Table 9-14.

Table 9-13 Neutral temperature for votes cast by non air-conditioned group

No.	Blanket type	*A* Thermal sensation votes	*B* Air temperature (C°)	*C* Operative temperature (C°)	*B-2(A)* Neutral air temperature (C°)	*C-2(A)* Neutral operative temperature (C°)
1	normal	1	31.2	31.5	29.2	29.5
2	normal	0	29.8	30.1	29.8	30.1
3	normal	-1	30.1	30.3	32.1	32.3
4	normal	-1	29.6	29.9	31.6	31.9
5	normal	0	30.2	30.4	30.2	30.4
6	normal	0	30.1	30.3	30.1	30.3
7	normal	0	29.6	29.8	29.6	29.8
8	normal	-1	29.5	29.7	31.5	31.7
9	normal	0	29.5	29.7	29.5	29.7
10	normal	0	29.5	29.7	29.5	29.7
11	normal	0	29.5	29.6	29.5	29.6
12	normal	0	31.0	31.2	31.0	31.2
13	normal	0	30.5	30.6	30.5	30.6
14	normal	0	29.7	29.8	29.7	29.8
15	normal	-1	29.1	29.3	31.1	31.3
16	normal	-1	29.1	29.3	31.1	31.3
17	normal	0	30.2	30.4	30.2	30.4
18	normal	1	31.0	31.2	29.0	29.2
19	normal	0	30.3	30.5	30.3	30.5
20	normal	0	30.4	30.6	30.4	30.6
21	normal	0	29.5	30.0	29.5	30.0
22	normal	1	30.5	30.7	28.5	28.7
23	normal	-1	29.7	29.9	31.7	31.9

Table 9-14 Average neutral temperature for non air-conditioned group

	Mean (C°)	Std. Deviation (C°)
Air temperature	30.2	0.9
Operative temperature	30.5	0.9

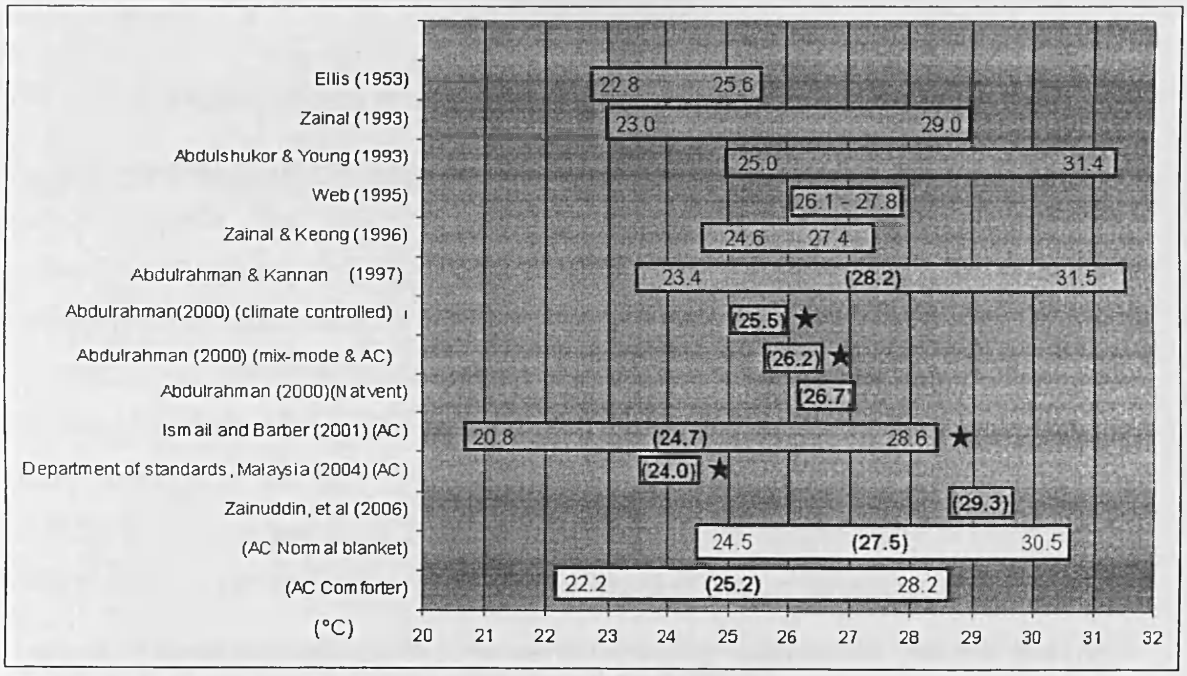
It is clear from the results that the average neutral temperature for people not using air-conditioning is higher than those who are using it. The neutral air temperature for this group (30.2°C) is 2.7°C higher than normal blanket group and 5.0°C higher than comforter group. It is also important to mention here that the use of forced convection is higher in this group (air speed 0.31 m/s) than the air-conditioned group (air speed 0.13m/s) (see Table 8-6).

9.5 *Discussions of findings*

The thermal neutrality values obtained are discussed in this section. The neutral temperatures and the comfort range are then used to evaluate the thermal conditions of air-conditioned bedrooms during night time occupancy in Malaysian homes.

9.5.1 Comparison with other studies

At the time of writing, there is no other field survey conducted in Malaysia focusing on thermal comfort of sleeping subjects (met 0.7). As such it is difficult to make direct comparison with findings by others. The comparison with findings from other studies in Malaysia as discussed in the literature review is shown in Figure 9-1.



Note: ★ indicate values for air-conditioned occupancy. values in bold and brackets are neutral temperatures.

Figure 9-1 Comparison with comfort range and neutral temperature from other studies in Malaysia

The neutral temperature values are higher than the standard specified in the publication by the Department of Standards [12] for air-conditioned spaces (non-residential) of neutral temperature 24°C. The difference is most likely due to the lower metabolic rate of the respondents in this study, i.e. sleeping. The neutral temperature for the whole air-conditioned population (26.8°C) is similar to the neutral temperature for naturally ventilated buildings proposed by Abdulrahman [13] (26.7°C). However the neutral temperature for comforter group (25.2°C) is slightly lower than the neutral temperature proposed by Abdulrahman [13] for climate-controlled occupancy (25.5°C). The neutral temperature for normal blanket group is higher than the neutral temperatures for air-conditioned occupancy from other studies. It is also higher than the neutral temperatures for naturally ventilated occupancy as proposed by Abdulrahman [13].

The classification of the bedrooms as a free-running building has been argued in section 3.1.3. If the study is assumed to be of the occupants of a free-running building (or naturally ventilated) space, the values for the comforter group is similar to the range proposed by Zainal for factory workers [14]. The range for both groups fall within the values proposed by Abdulrahman and Kannan [15] and Zainuddin [16] for naturally ventilated classrooms. However, even though the match is obvious, the difference in the assumption for the metabolic rates renders the comparison inconclusive.

9.5.2 Comparison with adaptive models

The neutral temperatures and comfort range established from the study are compared with two adaptive models discussed in the literature review (Auliciems'[17], Nicol and Humphrey's [18]). Since these models rely on outdoor conditions, the mean monthly outdoor temperatures during the study period need to be established first. The mean monthly outdoor temperatures during the study period are shown in Table 9-15. The mean monthly temperature during the whole period of study is found to be 28.7°C. The standard deviation is fairly small over the two months monitoring period (0.7°C). As such, this figure can be used to represent the mean monthly outdoor temperature for the whole of the cases gathered in this study.

Table 9-15 Mean monthly outdoor temperature during study period (source: Malaysian Weather Department (2005)

		Monthly maximum	Monthly minimum	Mean monthly
2004	Oct	32.3	23.9	28.1
	Nov	32.5	23.6	28.1
	Dec	32.0	24.0	28.0
2005	Jan	33.3	23.8	28.5
	Feb	34.4	24.4	29.4
	Mar	34.2	24.7	29.5
	Apr	33.8	24.8	29.3
	Average	33.2	24.2	**28.7**
	Std. Dev.			0.7

The adaptive model developed by Auliciems [17] for air-conditioned and naturally ventilated buildings is used to produce the neutral temperature for the study population.

$$\mathbf{T_n = 17.6 + 0.31(T_o)} \qquad \text{(equation 2-3)}$$

Where T_n is the neutral temperature and T_o is the monthly mean outdoor air temperature. Substituting the T_o value with 28.7°C from Table 9-15, the neutral temperature for the study population is:

$$\mathbf{T_n = 17.6 + 0.31(28.7)}$$

$$\mathbf{T_n = 26.5°C}$$

It is found that the neutral temperature produced by Auliciems' model is 26.5°C. This figure is close to the neutral temperature for whole study population (26.8°C). This figure overestimates the neutral temperature for the comforters group by 1.3°C but underestimate that of the normal blanket group by 1°C.

Comparison of the neutral temperature for the non-air conditioned group with the adaptive model for free running buildings is worth investigating. The model proposed by Nicol and Humphreys [18] for free running buildings is used for this analysis:

$$\mathbf{T_n = 13.5 + 0.54T_o} \qquad \text{(equation 2-4)}$$

Substituting 28.7°C for T_o :

$$\mathbf{T_n = 13.5 + 0.54(28.7)}$$

$$\mathbf{T_n = 29.0°C}$$

The neutral temperature proposed by this model is 29.0°C. This is lower than the neutral temperature for the non air-conditioned group (30.2°C). Again, the difference could be attributed to the lower metabolic rate specific to the current study, whereas the model was derived from various field studies, mostly investigating activities other than sleeping.

9.5.3 Comparison with PMV-PPD method

In many field surveys, a comparison with the PMV-PPD method is worth investigating. However, this is not attempted in the current study for the reasons discussed below.

Firstly, the thermal profiles of most of the cases in the study are of the transient, dynamic kind, whereas one of the main conditions for the application of PMV-PPD method is a steady state condition. Secondly, one of the problems faced by the current study is obtaining accurate information regarding the clothing articles worn by subjects when they go to sleep. The problem is of cultural nature and is discussed in more detail in Chapter 11. Another problem relating to this is the fact that the air speed value cannot be confirmed for each vote, due to the limitation of sensor placements in the bedrooms. Air movement in the bedroom is complex. The possibility of cooling by air movement over subjects could not be investigated accurately. Without accurate information of these two parameters of thermal comfort, it is reasonable to expect errors in the results produced by the PMV-PPD method.

9.5.4 Overcooling analysis

In this section, the level of overcooling in the bedrooms is assessed. A simple way of establishing this assessment is by comparing the average internal temperature found in the bedrooms with the comfort range established from this study. For this analysis, the concept of "less than optimum" is more appropriate than "acceptable". It can be argued that by using air-conditioners, occupants may choose to overcool the building unnecessarily, while maintaining their votes within acceptable limit by various adaptive actions. Since the objective of this analysis is to assess 'less than optimum' conditions rather than acceptability issues, the narrower comfort range established by applying 10%PPD criterion is the more appropriate criterion of evaluation.

The lower comfort boundary of air temperature value for comforter subjects established in section 9.4.2 (24.2°C) for < 10%PPD is used as a cut off value for lower optimum conditions. The numbers of households with average internal temperatures that fall on either sides of this value are analysed. The result is shown in Table 9-16. From the table, it can be seen that 38% of the households have their average night time internal conditions lower than the optimum comfort range established in the study.

Table 9-16 Number of households with average internal conditions lower than optimum comfort range

Average night time internal operative temperature (°C)	Number of households	Percent (%)
Less than 24.2°C	11	38
24.2°C and above	18	62
Total	29	100

However these findings do not give the whole picture of the actual thermal performance of the conditions found in the study. As has been established by the analysis of the thermal conditions in Chapter 8, the internal thermal conditions in the study follow a dynamic profile with significant temperature swings from the time the units are switched on at night, to the time they are switched off in the morning. As a result, even though the average temperature of a room is above 24.2°C, there is a possibility that in the early morning hours, the internal condition falls below this temperature.

The number of households with minimum internal temperature below the minimum value is now investigated. The result is shown in Table 9-17 below. It is found that around 76% of the rooms have their internal conditions, at some point during the occupancy period, falling below the optimum comfort range conditions. The results suggest that at some point during night time occupancy, the majority of the air-conditioned bedrooms in the study are over-cooled.

Table 9-17 Number of air-conditioned bedrooms with minimum internal conditions below acceptable condition range

Minimum Internal air temperature (°C)	Number of household	Percent %
Less than 24.2	22	76
24.2 and above	7	24
Total	29	100.0

9.6 Summary

The objective of the study is to establish the range of comfortable thermal condition for air-conditioned bedroom during night time occupancy. Votes cast on the ASHRAE 7 point thermal sensation scale are analysed in relation to environmental conditions recorded by the data logger. Analysis of acceptability based on votes cast on three central values of the scale revealed that around 40% of the votes indicate non acceptable condition.

The Griffiths method of analysis [8], revised by de Dear and Brager [9], is employed to establish the neutral temperatures and the results seem to agree with other studies, producing a value of 26.8°C. An investigation into the effects of the two types of blanket thicknesses reveals a significant difference in the neutral temperatures. The neutral temperature for the comforter group is found to be 25.2°C, and the value for normal blanket group is 27.5°C. The distinction of blanket type has to be made clear when conducting thermal comfort study of air conditioned occupancy in the bedrooms. The comfort range for the normal blanket group is between air temperature of 24.5°C and 30.5°C, while the comfort range for the comforter group is between air temperature 22.2°C and 28.2°C

The results are compared to the findings from other studies in Malaysia. However, this posed a problem. Firstly the thermal comfort for a subject with sleeping activity has not been studied by others. Secondly, the classification of the occupancy type (whether it is a mixed mode, air-conditioned or naturally ventilated) cannot be determined positively in the current study. Therefore, even though the results seem to agree with other findings, direct comparison with these studies is not conclusive.

The results are also compared to the figures obtained by the adaptive models discussed in the literature review. The neutral temperature for comforter group is found to be similar to that of the theoretical model proposed by Abdulrahman [13] for air-conditioned occupancy. The results are also compared with two adaptive models. The neutral temperature for the study population is similar to that proposed by Auliciems [17]. However this model overestimates the value for the comforter group by 1.3°C and underestimates the value for normal blanket group by 1.0°C. The model for free running buildings developed by Nicol and Humphreys shows that the occupancy does not resemble that of free running type.

Evidence of unacceptable conditions and overcooling is found. Around 39% of the votes cast falls lower than -1 vote category, indicating unacceptable cold conditions. Applying the range of optimum comfort conditions established in the study against the internal conditions monitored, it is found that 38% of the bedrooms have their average internal conditions fall below this range (less than 24.2°C). 76% of the bedrooms are found to have their internal conditions, at some points during the occupancy period, fall below the optimum range established in this study.

The difference in the neutral temperature between the two blanket types has implications on cooling energy demand. In the next chapter, a simulation study is conducted to assess the different energy demands and the corresponding economic and environmental impacts by the use of different blanket types.

9.7 References

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10 Energy Simulation Study

10.0 Introduction

Different operational temperatures between cases employing normal blankets and those employing comforters imply potential reduction in energy use by adopting appropriate blanket thickness. In this chapter, the differences in the energy need for cooling are estimated by simulating the different temperature settings derived from the different blanket groups established in this study. Since various technical information required for annual energy demand is not investigated in this study, the energy analysis focuses on space cooling load only and not annual energy demand.

10.1 Simulation Model

The difference in space cooling load between the two blanket groups is estimated by simulating the different operating scenarios, established in chapter 8 and chapter 9, using ECOTECT software package version 5.2 (www.squ1.com). Weather data for Kuala Lumpur (3°8' N, 101° 42' E) from EnergyPlus [1] is used as it is more accurate compared to the one that is supplied by the ECOTECT publisher.

10.1.1 Dwelling model

The model house used in this study is based on the typical double storey terrace house found in the study (described in section 5.3.3), with a total floor area of 120.3m^2. (See Figure 10-1). The simulated zone is the master bedroom situated on the upper floor with a floor area of 22.3m^2. The construction of the house is shown in Table 10-1. The master bedroom in the double storey terrace is located on the first floor facing south.

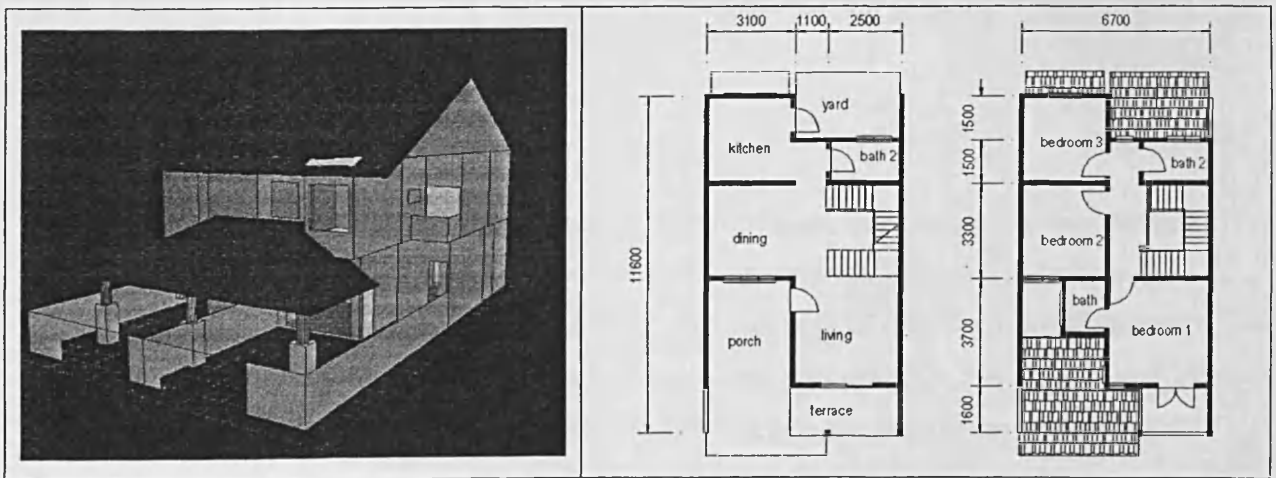

Figure 10-1 - The model house

Table 10-1 Construction of model house

Elements	Construction	U values (W/M^2 K)
Party Walls	225mm brick with 10mm plaster either side.	2.62
Internal walls	110mm brick with 10mm plaster either side.	2.72
Windows	Single glazed timber frame	5.0
Ceiling	10mm suspended plaster board ceiling, plus 50mm insulation, with remainder (150mm) joists as air gap.	0.5
Ground Floor	100mm thick concrete slab on ground plus ceramic tiles.	1.821
Upper Floor	100mm thick suspended concrete floor plus ceramic tiles and plaster ceiling underneath.	2.9
Roof construction	Clay tile roof on timber trusses.	1.823

The choice of this dwelling type represents 20% of the study sample. The simulation is conducted for the cooling of the master bedroom. This bedroom is chosen as it is the room where air-conditioning is used, as found in all the cases monitored. In terms of thermal performance, the room is similar to that found in all the other houses due to the fact that the room is of similar size and construction materials, and situated beneath similar roof construction. It can thus be argued that the difference in thermal performance between this room and the rooms in other type of dwellings in the study is small.

10.2 Simulation parameters

The air-conditioning is set to operate from 10pm to 5am in the morning. This period of operation is established from the findings of the survey discussed in chapter 8. In deciding the temperature settings for the two blanket groups, three different scenarios are simulated:

1. Neutral temperature

The neutral temperatures for both blanket groups established by the revised Griffiths method are used as the temperature settings. Hence the temperature settings used are 25.2°C for comforter group and 27.5°C for normal blanket group. The simulation of these settings seek to establish the differences in space cooling loads between the two blanket groups, assuming people would choose the thermal conditions that would produce a 'neutral' sensation.

2. Preferred temperature

As had been explained in Chapter 2, the assumption that people would seek thermal neutrality has been proven inaccurate. It can be argued that, presented with the opportunity to choose their own environment, people will seek to be in the conditions they prefer, rather than the condition that produce a 'neutral' sensation [2]. Due to this, simulation for 'preferred' setting is conducted. Researchers who conducted field studies trying to establish preferred temperatures found evidences that people in colder climates prefer warmer conditions, while people in warm climates prefer temperatures colder than neutral. An example is a study by Andamon et.al [3] in the Philippines, who found that the acceptable[11] sensation is clustered around the vote -1 (Slightly cool). Hwang et.al. [4] found that 32% of students in an air conditioned classroom in Taiwan (hot and humid climate) prefer to be in colder condition, even though they vote neutral for the condition they currently experiencing.

In this exercise it is decided to use the lower acceptable boundaries for 10%PPD (at Tsv = -0.5), as established in Chapter 9 (see table 9-11) as the preferred value. Therefore for each blanket group, the preferred temperature is 1°C lower than neutral. It follows that the temperature setting for the comforter blanket group is 24.2°C while it is 26.5°C for the normal blanket group

3. Household group settings

A third scenario, simulation of the average monitored internal temperatures as acquired from the data logger is simulated. Analysis of the internal conditions of the rooms reveals that there is a difference in the average internal temperature between households where all occupants use comforters and those in which occupants do not. The households in which all occupants used comforters have an average internal temperature of 22.1°C and those in which occupants did not, have an average internal temperature of 24.9°C (See Table 8-25). It is proposed here that these values can be used as the temperature settings for the simulation. It can be argued that this is the most

[11] In this section, the term 'acceptable' is interchangeable with 'no change' in terms of preference, since they relate to sensations of same category in acceptability scale and preference scale respectively. (See table 2-1).

realistic scenario since the values established are gathered empirically from the study.

The corresponding temperature settings for the two cases are shown in Table 10-2. The lower range is set to 0.0°C for all cases although the internal conditions never get lower than 15°C. The value 0°C is chosen so that heating is not simulated since none of the units have heating capability.

Table 10-2 preferred temperature for two blanket types

Blanket type	Neutral temperature (PMV = 0)	Preferred temperature/Temperature setting (-1.0°C)	Average internal temperature from monitored data (household blanket group)
Comforter	25.2°C	**24.2°C**	**22.1°C**
Normal blanket	27.5°C	**26.5°C**	**24.9°C**

10.2.1 Operational parameters

The summary of building use parameters is shown in Table 10-3. Since the operation is during night time, the same operation pattern is applied between weekdays and weekends.

Table 10-3 Summary of building use pattern

<table>
<tr><td>Occupants</td><td colspan="3">2 people Sedentary. The produced heat is 70 w sensible and 45 w latent per person (sedentary) (CIBSE Guide A 2006)</td></tr>
<tr><td>Lighting</td><td colspan="3">Lighting gains are 3 W/m² and operating between 1900 and 0000. (2 Fluorescents 32W)</td></tr>
<tr><td>Cooling operation</td><td colspan="3">Between 2200 and 0500</td></tr>
<tr><td>Air infiltration</td><td colspan="3">Air change rate of 0.5 per hour</td></tr>
<tr><td rowspan="4">Temperature setting (Upper range)</td><td>Temperature setting scenarios</td><td>Comforter (°C)</td><td>Normal blanket (°C)</td></tr>
<tr><td>Neutral</td><td>25.2</td><td>27.5</td></tr>
<tr><td>Household groups settings (monitored)</td><td>22.1</td><td>24.9</td></tr>
<tr><td>Preferred</td><td>24.2</td><td>26.5</td></tr>
<tr><td>Temperature setting (Lower range).</td><td colspan="3">0°C</td></tr>
</table>

10.3 Results

The monthly cooling load for the bedroom for different blanket types and temperature setting scenarios are shown in Table 10-4. The load reduction by employing a normal blanket, instead of a comforter, is shown in the last row of the table.

Table 10-4 Monthly cooling load by different blanket types (values in kWh)

Temperature settings scenario	Neutral		Preferred (lower boundary for 10%PPD)		Household types	
Blanket type/household type	Comforter	Normal	Comforter	Normal	All occupants used comforter	Not all occupants used comforter
Temperature settings	25.2°C	27.5°C	24.2°C	26.5°C	22.1°C	24.9°C
Jan	75.3	36.8	97.3	64.8	171.6	80.6
Feb	74.6	39.7	99.7	59.9	171.2	81.0
Mar	90.3	50.7	116.9	71.2	194.9	96.8
Apr	90.3	61.6	122.3	69.1	200.3	98.7
May	103.5	63.3	138.7	75.5	219.4	113.2
Jun	93.2	61.7	122.5	72.0	196.7	101.0
Jul	86.2	59.2	114.2	69.7	192.5	93.1
Aug	82.2	46.1	107.2	67.7	183.6	88.0
Sep	86.0	46.2	113.0	67.6	189.7	93.0
Oct	72.3	25.1	91.5	64.6	165.7	76.4
Nov	72.5	38.3	95.5	60.7	169.8	77.5
Dec	73.3	21.7	96.4	60.5	173.4	78.2
Total	999.6	550.3	1315.2	803.2	2229.0	1077.5
Cooling Load difference (kWh)	449.2		512.0		1151.5	
(saving percentage)	45%		39%		52%	

From the table, it can be seen that the largest difference between the different blanket types can be found when simulating different temperatures obtained from monitored data (1,151.5kWh), a reduction of 52%. Simulation of Neutral and preferred temperature yields similar difference (45% and 39%). This could be explained partly by the fact that the difference between temperature settings of different households (aggregated between the two blanket types) is higher (2.8°C) compared to the different temperature settings in the other two scenarios (2.3°C)

10.4 Discussion of findings

The different cooling loads between different operating scenarios suggest that energy use for cooling can be reduced by choosing an appropriate blanket thickness when sleeping in an air conditioned bedroom. It can be proposed here, that energy saving is possible if normal blankets are used instead of comforters as sleeping covers in air conditioned rooms.

As had been suggested in Chapter 5, the reason why many people use comforters in Malaysian homes maybe of a psychological or socio-cultural nature (see Chapter 5). The finding may nevertheless be used to support the case for using normal blankets as sleeping coverings in air conditioned rooms in Malaysia.

10.5 Summary

A simulation exercise is conducted to assess the difference in cooling load for an air conditioned bedroom between a normal blanket user and a comforter user. Three different scenarios of operation were conducted, using different values from neutral temperature, preferred temperature and average temperature monitored. It is found that by switching sleep cover from a comforter type to a normal blanke type, the cooling load for the bedroom can be reduced by as much as 52%. The figures established could be used to educate the public to choose appropriate covers for occupancy in air-conditioned bedrooms in order to reduce energy use in this sector.

10.6 References

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11 Limitations of study

11.0 Introduction

This section discusses the limitations of the study which might restrict the generalisation of the findings to all Malaysian households with air-conditioning. There are some limitations with respect to the data acquisition and analysis that may affect the accuracy of the results. The discussion focuses on the problems found in the study with the objective of pointing towards ameliorative measures in conducting similar studies in the future.

11.1 Household types distribution

The first problem faced by the current study is in getting a sample size representative of various house types and income levels. This categorisation is identified as a significant factor influencing domestic air-conditioning use pattern [1]. The main problem in this regard is to secure willing participants from various house types and income bands. None of the households monitored responded to the letter invitations. All participating households were acquired by direct personal approach to people who have personal contacts with the author or through introduction by a third party who is a mutual contact of both the author and the participants.

This problem is not unique to the current work alone. Similar problems were faced by a research effort by CETDEM (Centre for Environment, Technology & Development, Malaysia), a non-governmental organisation set up to promote energy efficiency in homes in 2006 [2]. Failing to secure the required number of samples from joint collaborations with various residents associations, the team had to approach personal contacts and ask existing participants to encourage their friends to sign up for the research.

This results in samples distribution which does not have similar mix to the national household distributions of income groups and house types. In the study, some of the major household types do not have enough number for a meaningful statistical analysis to be carried out. As a result, comparative analysis of household types and income bands cannot be established conclusively in this study.

11.2 Limitation in data acquisition

Another set of problems lies in acquiring accurate value of some of the thermal comfort parameters. This is discussed as follows.

11.2.1 Air movement measurement

In this study of crucial importance is the air movement over the body of a sleeping subject. The measuring instrument could not be placed accurately at this position due to the impracticality of the task. In some cases, it is not possible to get to the closest possible location to the subject due to the arrangement of furniture. As such, the effect of air movement on the thermal sensation cannot be determined conclusively. Although, on average, the results show minimal air movement, the possibility of subjects employing direct forced convective cooling over a supine body cannot be analysed accurately.

11.2.2 Air change rate

Another difficult task in the study was to determine accurate information on the values of air change rates which affect the performance of air-conditioning units. It was not possible to determine the size of all openings in a room during the limited time available at the commencement of each monitoring session. A consideration used here, is to minimise the time and level of intrusions into people's private space.

Even though air exchange between inside and outside can be assumed to be minimal because windows are not opened during the night, the exchange between the internal spaces, which has an effect on the internal condition, is not easy to ascertain. The problem lies in the fact that the air conditioning takes place in the bedroom and not the whole house. The resulting air-change rate from the actions of opening and closing the door of the bedroom, which affect the unit's performance and the thermal conditions, is difficult to assess.

11.2.3 Personal clothing value

One of the most pertinent problems in thermal comfort field studies is determining the insulation value of subjects. The classification of clothing types in a standard table could not possibly deal with the variations in thickness of articles under the same description. Another factor is the cultural stigma faced during the study when ascertaining the clothing people wear when going to bed. In one case, a respondent threatened to lodge a report to the police because he believed the enumerator was probing 'obscene' issues. Following this, the procedure has to include the verbal consent of respondents prior to further questioning regarding this issue. This problem and a few other incidents also result in the decision to exclude articles such as panties, underwear and bra from the list of article of clothing.

In this study, the use of covers further complicates the matter. The grouping of subjects between only two groups of insulation level, namely normal blanket and comforter might have overlooked the possibility of differences between various comforter thicknesses and the extent to which the covers are used throughout the monitoring period. Ideally, the blanket analysis should be carried out with visual recordings of people sleeping, so the level of use of blankets can be assessed accurately. However, such a highly intrusive investigation of real life cases is difficult to arrange with the limited time and resources available.

11.3 Limitation in analysis

Thermal comfort analysis and energy use prediction conducted in Chapter 9 and Chapter 10 provide a rough estimation of the real situation. Another set of problems which affect the accuracy of the result is in analysing the data gathered from the study. This is discussed as follows:-

11.3.1 Establishing temperature settings

A possible inaccuracy in the study is in the estimation of the energy demand from the two blanket groups. The reliance on the use of 10% PPD as the lower boundary temperature as the preferred temperature and hence, the temperature setting, might not be accurate. Thermal preference analysis should be able to give more accurate figures. The underlying assumption taken in the study is that since people have control over the thermal condition (by means of air-conditioning units), the thermal preference should not be an issue. However in retrospect, this assumption overlooks the fact that there might be only one subject who decides the control of the unit at a particular time. As such, it might be useful to ask the thermal preference of the other subject sharing the room.

11.3.2 Night time thermal comfort model

Ideally, a thermal comfort model relying on ambient external or internal air temperature should be the outcome of such a study. However, this could not be attempted for the reasons already discussed above.

The coefficient of performance of an air-conditioning unit plays an important role in determining the relationship between energy consumption, resulting internal condition and hence thermal sensation, which in turn detrmine the adaptive behaviour of occupants. In real life monitoring, such as in the current study, factors affecting the performance of the units, such as maintenance issues, air change rates, different positioning of units, are difficult to assess.

In addition to this, the different operational patterns and adaptive behaviour between cases makes the task of constructing a reliable model even more complex and difficult. To produce a scientific model, a more comprehensive and rigorous data acquisition procedure is needed. A better sample distribution representing various household types and income levels, investigation into air-change rate, maintenance issues and other operational issues should also be attempted.

11.3.3 Air conditioner performance

It would be desirable to have a clearer picture of the engineering aspect of air-conditioners in this study. However, detailed technical explanations of the various thermal profiles could not be offered since a lot of necessary information was not available for this purpose. Nevertheless, where it is possible, technical explanation has been offered to explain one or two cases. However, the explanation for the whole sample is not attempted. The thesis focus more on people's experience and perception of thermal comfort in the air conditioned rooms.

11.4 Improvement to the current work

Having concluded the study and analysing the problems faced, as discussed above, it is worth looking into necessary changes to the methodology used, should a similar study be attempted again.

The reasons for people's decision to adopt the use of air-conditioning in their homes should be investigated. Since the study suggests that the differences in thermal perception and adaptive behaviour between groups or individuals are due to reasons not limited to a physiological nature, socio cultural or psychological insight might be obtained from asking such questions.

Also of importance, is to understand the reasons people opt for comforter type of blankets. The answer to this might give an answer to the question whether it was psychologically motivated, or due to unintended overcooling of the internal conditions as has been found in some cases in the study.

A more controlled experiment can be done by asking people to sleep in a laboratory set up. The internal thermal condition can then be varied with greater precision and people's responses in terms of thermal vote, as well as blanket use, can then be correlated more precisely, and a generalisation to the wider population is possible. In such a setup, video recording of people's sleeping positions; extent of cover use etc could be arranged. This would overcome the problem of establishing actual insulation values needed for PMV investigation.

11.5 Summary

To establish a more accurate picture of the use of night time air conditioning for the whole population, a more rigorous and comprehensive study is needed. The problems discussed above, properly addressed, should provide any researcher intending to conduct a similar study in the future with a more refined investigative technique which could produce more accurate results.

The problems of producing a theoretical model from the data gathered in the study have been discussed. A theoretical model, however, is not crucial for the purpose of the current study, which aims to establish thermal neutrality and acceptability for night time air-conditioned occupancy.

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12 Conclusions

This chapter summarises the key findings of the study. First the main findings of the study are presented. Following this, considerations on adaptive behaviour and energy saving potential in the use of air-conditioners in Malaysian homes are made. The contribution of this study to the overall picture of thermal comfort study in Malaysian homes is also highlighted. The chapter ends by suggesting further works to provide a better understanding of air-conditioning use in Malaysian homes, and for the optimum use of energy in this growing sector of energy consumption in Malaysia.

12.0 Characteristics of domestic air conditioners in Malaysia

The percentage of households employing the use of air-conditioners is rising. The resulting increase in energy demand has been established by others and examined in the literature review. Apart from information on the number of air-conditioning units in Malaysian homes and the resulting energy demand, no other information is found in the literature regarding the use of this cooling appliance in Malaysia. The preliminary survey conducted for the study managed to fill this information gap by establishing the characteristics of air-conditioning systems employed in the domestic sector.

A majority of the houses in the preliminary study and all of the houses in the main monitoring study use single split air-conditioning units of between 1hp (750W) to 2 hp (1.5kW). It is found that most households have only one or two units installed. In all cases, it is in the bedrooms where the units are installed.

12.1 User behaviour

It was found that most of the units are used extensively during the night. On average, the units were turned on when the internal temperature was 29.4°C and turned off when it gets to 24.0°C.

The interruption of sleep, in order to carry out adjustment, was found in 45% of the cases monitored. Even in cases where a timer is used for switching off, in 33% of these, people still have to carry out adjustments during normal sleeping hours.

The use of a comforter or quilt type blanket was investigated. In the preliminary survey and in the main survey, comforters are never used by households without air-conditioning. Even within households that do use air –conditioners, the people who use normal blankets form the majority of the sample population. Hence it can be concluded that the use of comforters is not a necessity in the Malaysian climate. It can thus be proposed that the reasons could possibly be psychological or socio-cultural.

Rational thinking suggests that the choice of blanket thickness is a result of the thermal conditions experienced by people. However, it can be proposed here that the phenomenon is reversed in this situation. Since the internal conditions can be controlled by occupants, it is the choice of blanket that dictates the thermal conditions they choose. This is illustrated by the results from the investigation into the internal temperature when the occupants first operate their units, the trigger temperature. It was found that these trigger temperatures were not significantly different between the two types of household (normal blanket users and comforter users) when the occupants decided to start the operation of the units.

12.2 Environmental conditions of air-conditioned bedrooms during night time occupancy in Malaysian homes.

The internal conditions of these rooms during air-conditioning use were found to be on the cold and dry side. Evidence of overcooling, especially during the early morning hours can be found in the study. This reduction of temperature was also accompanied by a reduction in humidity level, due to removal of moisture during condensation in the cooling unit.

Another significant finding arising from the study is that the thermal conditions of air-conditioned bedrooms are dynamic. In around 40% of the cases in the main survey, internal conditions did not stabilise around a set temperature. In these cases, the conditions keep getting cooler towards morning. This has the effect of sometimes causing the internal temperature to get below the lower comfort boundary range during normal sleeping hours. This could be one of the factors contributing to the incidence of mid sleep adjustments in 45% of the cases.

12.3 Thermal comfort in air conditioned bedroom

The study manages to establish the neutral temperature and the comfort range for night time occupancy in an air-conditioned bedroom. A significant difference is found between the neutral temperature value for the comforter users and that of normal blanket users. The neutral temperature for cases using normal blankets is 27.5°C and for cases employing comforters is 25.2°C, a difference of 2.3°C. Monitoring analysis of the environmental conditions between households employing comforters and the rest also reveals similar findings. The actual average internal air temperature of households where all occupants used comforters is found to be cooler (22.1°C) than other households (24.9°C), a difference of 2.8°C.

Analysis of the thermal votes gathered reveals that around 45% of these fall lower than the three central categories of acceptable condition votes. Using the lower boundary of optimum range established for this study as the minimum acceptable condition, around 40% of the households have their average internal conditions overcooled. Around 76% of the bedrooms have air temperatures falling below the optimum comfort level, at some point during the occupancy period. These results suggest that appropriate control operation had not been widely practised in the study population.

12.4 Adaptive behaviour findings

The study shows conclusively that the neutral temperature of a population not only depends on climatic condition or specific occupancy type, as most adaptive models tend to generalise, but it also depends on personal adaptations, such as the choice of blanket thickness. When typical adaptations can be identified within a large population, these need to be taken into account when establishing its thermal neutralities, or when developing its adaptive model.

The principle of an adaptive approach to thermal comfort can be defined as "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" [1]. If the paradigm offered by this principle is adhered to, perhaps the establishment of a comfort range in a field study is of secondary importance, since people will take corrective action to be comfortable in any thermal conditions they experience.

Perhaps a more important issue that can be raised by this study is the range of adaptation they take as corrective measures, which will indicate whether or not the thermal conditions provide optimum conditions for occupancy, balancing a need for comfort and energy use.

Investigation into adaptive actions taken by the subjects reveals a less than optimum situation. The study shows that there is a dilemma in establishing a comfort range for the population. Although people might eventually express comfort in an air-conditioned bedroom, their adaptive actions indicate that the thermal condition is less than satisfactory, since their adaptive actions:

i. Interrupt their sleep.
ii. Use more energy than necessary.

The question remains, should this scenario be regarded as acceptable, since the occupants express satisfaction with the performance of their units? Or, should acceptability analysis include 'best practice' behavioural assessment that takes into account optimum use of energy?

12.5 Energy saving potential

Based on the results obtained from the study, it can be proposed that energy saving in the use of air-conditioning in Malaysian homes can be achieved in two ways. First, if an effective control strategy is introduced, energy can be saved by the reduction of the incidents where internal conditions fall below the lower comfort boundary established in Chapter 9. As had been established in the analysis of environmental conditions in chapter 8, the time it takes for some cases to reach the stabilised phase is long. As such it is difficult for users to decide on an appropriate temperature setting since the set temperature is only attained long after they go to sleep. In the worst scenarios, the room temperature never actually settles around a fixed temperature.

Secondly, the difference in the neutral temperature of 2.3°C between the two groups of different blanket types suggests that, the use of a normal blanket as opposed to a comforter cover can result in energy saving. A simulation study was conducted to assess the implications of employing different blanket types on cooling energy. It is found that as much as 52% of the cooling load can be reduced by choosing a normal blanket instead of a comforter as sleeping covers.

12.6 Contributions of study

The study provides valuable information regarding the use of air-conditioners in Malaysian homes. Up to the writing of this work, no other study on thermal comfort of sleeping subjects or nighttime occupancy in Malaysia has been found in the literature review. The characteristics of air-conditioning use in Malaysian homes regarding unit types, number of units per household, operation patterns and type of space being air-conditioned are also new information established from this study.

Information regarding the thermal conditions of air-conditioned rooms in domestic settings is also the first for Malaysia. Overcooling, large temperature swings and instability of the internal environmental conditions are problems identified conclusively from this study. These will be valuable in providing the background framework from which any future in-depth study would benefit.

The establishment of thermal neutralities in air-conditioned bedrooms during night time occupancy provides new information for thermal comfort field studies in the region. The identification of types of adaptive behaviour also highlights problems with the thermal conditions of air conditioned bedroom in Malaysian homes.

12.7 Recommendation for further works

The current study focuses on the use of air-conditioning in bedrooms and only during night time occupancy. To improve the design of air-conditioning units, the whole picture of air-conditioning use in home, encompassing its use in other spaces and during daytime will be necessary.

Continuing economic growth, and hence income per capita, compounded by the reduction in unit price due to economies of scale in production may yet give rise to continuing, increasing growth rate of the use of air-conditioners in Malaysian homes. Another possible driver for the increase is the increasing global temperature from the global warming phenomenon that is happening currently. Investigation into the accelerated growth of air conditioners in Malaysian homes resulting from these drivers will provide a better picture of the impact on energy use in this sector.

There is a need to improve the response time of the air conditioning units in achieving the desired comfort condition, hence eliminating the problem of suboptimum temperature setting chosen by people. This might not necessarily be in the form of increasing the power of the unit. A possible improvement in the design of the air-conditioning system would be to ensure a shorter response time for the units to bring the internal conditions to within comfort range, so the initial temperature setting could reflect actual desired conditions. To achieve this, a more controlled study is needed, especially on air distribution pattern in air-conditioned rooms and its effect on the comfort sensation.

The choice of blanket type affects the desired temperature selected by occupants. It has been argued earlier that the reason for this choice is not physiological. A social or psychological study on why people use comforters in air-conditioned bedroom is needed. The information will be valuable in formulating how to introduce corrective measures such as educating the public on choosing appropriate covers in order to save energy.

The adaptive behavior identified in this study highlights another dilemma in thermal comfort studies. If occupants express satisfaction with a thermal condition and yet their adaptive actions result in less than ideal conditions, is it acceptable? A research worth investigating can be proposed here, where the adaptive actions observed in an occupied space are used as a measure of performance of its comfort provision.

12.8 Conclusion

The study achieved the objectives set out at in the introduction, i.e. to investigate the environmental conditions and user behaviour in the use of air conditioners in homes, and to establish the thermal comfort conditions for occupancy in air-conditioned homes in Malaysia. Even though the focus is limited to bedroom use during sleeping hours, this is the place and time where most domestic air-conditioners are used.

It is hoped that the findings provide a solid base upon which future work in improving the design of air-conditioning units for domestic use in terms of energy efficiency and comfort provision may be built.

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Appendices

Appendix 1: Preliminary survey form (main group)

Appendix 1: Survey form of the main group

Sample No	Date		Enumerator

A. DESCRIPTION OF PROPERTY

1. HOUSE NO :	2. STREET NAME :	3. ETHNIC:

4. HOUSE TYPE:

1	Terrace 1 storey (Intermediate)		5	Semi-detached 1 storey		
2	Terrace 1 storey (corner)		6	Semi-detached 2 storey		
3	Terrace 2 storey (intermediate)		7	Multi storey (intermediate) (level)		
4	Terrace 2 storey (corner)		8	Multi storey (end) (level)		

5. HOUSE CATEGORY

1	Low cost		2	Medium Cost		3	High cost	

6. ORIENTATION OF ENTRANCE FAÇADE

1	North		5	North east	
2	South		6	South east	
3	East		7	North West	
4	West		8	South West	

7. SHADING LEVEL (USE THE SCALE):

Exposed-1 Lightly Shaded-2 Heavily Shaded-3 Party Wall-4

1	Front		3	Left	
2	Right		4	Back	

8. OWNERSHIP:

1	Own		2	Rental		3	Others (describe):

9. COST OF PROPERTY WHEN BOUGHT: RM ....

10. YEARS OF RESIDENCE AT THE PROPERTY:..........................YRS

11. RENOVATED FEATURE

1	No renovation		4	Porch/terrace	
2	Kitchen extension		5	Bedroom Addition	
3	Living room extension		6	Other (describe)	

B. DESCRIPTION OF HOUSEHOLD

12. TOTAL HOUSEHOLD INCOME RM.................

13. NO OF PEOPLE IN THE HOUSE DURING WEEKDAYS (Please state number)...............

	Time	Morning	Afternoon	evening
1	Weekdays			
2	Weekend			

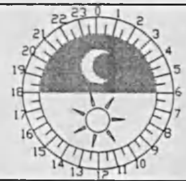
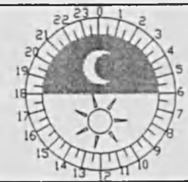
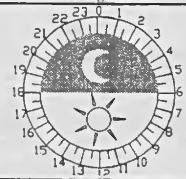
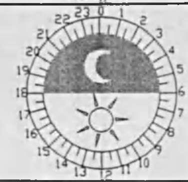
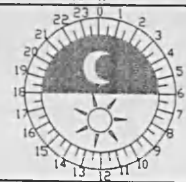
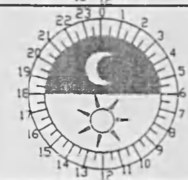
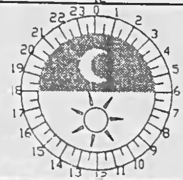
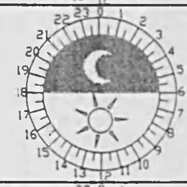
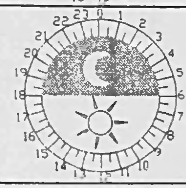
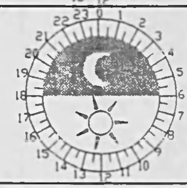
14. WHAT IS YOUR AVERAGE MONTHLY ELECTRICITY BILLS?

RM...................

C. DESCRIPTION OF SYSTEM

Sample no:

15. HOW MANY UNITS OF AIR CONDITIONING DO YOU HAVE? .... (Please describe each unit below)

a. Room (size (feet))	HP/Btu	Type*	Model/ brand name	When Installed	Recent use 1- Everyday 2- Often 3- Occasionally 4 -Never	Timer used? (yes/no)	Temperature setting		Weekdays use	Weekends use	Use Index
							Day	Night			
Living Room (........x......)											
Master Bedroom (........x......)											
Bedroom 1 (........x......)											
Bedroom 2 (........x......)											
(.................) (........x......)											

*SU= Split unit, MSU=Multisplit unit, WU = Window unit.

D. GENERAL USE PATTERN

16. HOW OFTEN DO YOU USE PROFESSIONAL HELP TO SERVICE YOUR UNITS?

17. WHAT KIND OF MAINTENANCE DO YOU DO YOURSELF?

18. HOW OFTEN DO YOU DO THIS?

19. PASSIVE COOLING MEASURE(S) ADOPTED:

1	Awning			5	Shady tree(s)	
2	Tinted Reflective glazing			6	None	
3	Roof insulation			7	Other (describe)	
4	Wind turbine					

20. WHAT FACTORS YOU TAKE INTO CONSIDERATION REGARDING THE USE OF AC?

		Very Important--------not important				
		1	2	3	4	5
1	Health hazard					
2	Electricity Bills					
3	Environment					
4	Comfort					

21. DO YOU INTEND TO BUY MORE UNITS?

1	Yes		2	No	

22. IF YES, HOW MANY?

23. ARE YOU HAPPY WITH THE PERFORMANCE OF THE UNITS?

1	Yes		2	No	

24. IF NOT, WHY?

....

E. COMFORT LEVEL IN AIR CONDITIONED ROOM

(To be answered directly by the user(S) of air conditioned bedroom)

Respondent	A	B		A	B
Profession:			Age:		
Gender:			Health:		

25. WHEN YOU USE AIR CONDITIONING IN THE BEDROOM, DO YOU USE A BLANKET TO GO TO SLEEP AT NIGHT?

		A	B			A	B
1	No Blanket at all			3	At certain time of the night		
2	Use it all night long			4			

26. WHAT TYPE OF BLANKET DO YOU USE?

		A	B			A	B
1	No Blanket			3	Thick sheet		
2	Thin Sheet			4	Comforter		

27. WHO NORMALLY HAS THE SAY ON THE TEMPERATURE/FAN SETTING IN THE ROOM?

1	A			3	Compromised setting	
2	B			4	Anyone	

28. WHAT ARTICLE OF CLOTHING DO YOU WEAR TO SLEEP?

		A	B			A	B
1	No shirt			13	Night Gown (maxi)		
2	Singlet			14	Shorts		
3	T-shirt short sleeve			15	Bermuda		
4	T shirt Long Sleeve			16	Pajamas Bottom		
5	Sweater			17	Track Bottom (Thin)		
6	Pajamas (top)			18	Track Bottom (Thick)		
7	Kaftan			19	Kain Batik/Pelikat		
8	Night gown (mini)			20	Socks		
9	Night Gown (midi)			21	Others (Please Describe)		

29. WHEN THE AIR CONDITIONING IS ON, DO NORMALLY YOU FEEL:

	Hot	Warm	Slightly warm	Ok	Slightly cool	Cool	Cold
	3	2	1	0	-1	-2	-3
A							
B							

30. PLEASE RATE THE NORMAL AIR QUALITY WHEN THE AIR CONDITIONING IS IN USE:

	Very Dry	Dry	OK	Stuffy	Very stuffy
	2	1	0	-1	-2
A					
B					

31. DO YOU USE ELECTRIC FAN AT THE SAME TIME YOU USE AIR CONDITIONING?

1	Always			3	Occasionally	
2	Sometimes			4	Never	

32. WHAT DO YOU NORMALLY DO WHEN IT'S GETTING TOO COLD? (TICK ONE OR MORE)

		A	B			A	B
1	Never too cold			6	Close/open window		
2	Adjust the temperature setting			7	Pull up blanket/Use heavier blanket		
3	Adjust the units fan speed			8	Just turn it off		
4	Use more clothing			9	Other (describe		
5	Switch off the unit and use electric fan						

Script: Thank you for your cooperation. In gratitude, we would like to present you with a small token for your help. On top of this survey, we will conduct a one-week monitoring of selected houses. In this monitoring we will leave the respondent with a datalogger for a week. It is a small device which will record the temperature and humidity at 5 minutes interval. We would also require a form to be filled on a daily basis. In this regard we would like to ask you:

33. ARE YOU WILLING TO TAKE PART IN OUR ONE WEEK STUDY?

1	Yes			2	No	

Appendix 2: Preliminary survey form (control group)

Appendix 2: Preliminary survey form (control group)

Sample No	Date	**control**	Enumerator

A. DESCRIPTION OF PROPERTY

1. HOUSE NO :	2. STREET NAME:	3. ETHNIC:

4. HOUSE TYPE:

1	Terrace 1 storey (Intermediate)		5	Semi-detached 1 storey	
2	Terrace 1 storey (corner)		6	Semi-detached 2 storey	
3	Terrace 2 storey (intermediate)		7	Multi storey-intermediate) (LEVEL)	
4	Terrace 2 storey (corner)		8	Multi storey -end) (level)	

5. HOUSE CATEGORY

1	Low cost		2	Medium Cost		3	High cost

6. PASSIVE COOLING MEASURE(S) ADOPTED:

1	Awning		5	Shady tree(s)	
2	Tinted Reflective glazing		6	Other (describe)	
3	Roof insulation		7	None	
4	Wind turbine				

7. OWNERSHIP:

1	Own		2	Rental		3	Others (describe):

8. COST OF PROPERTY WHEN BOUGHT: RM ....

9. YEARS OF RESIDENCE AT THE PROPERTY:..........................YRS

10. RENOVATED FEATURE

1	No renovation		4	Porch/terrace	
2	Kitchen extension		5	Bedroom Addition	
3	Living room extension		6	Other (describe)	

B. DESCRIPTION OF HOUSEHOLD

11. TOTAL HOUSEHOLD INCOME RM..................

12. NO OF PEOPLE IN THE HOUSE DURING WEEKDAYS (Please state number)...............

	Time	weekdays	w/end
1	Morning		
2	Afternoon		
3	Evening		

13. WHAT IS YOUR AVERAGE MONTHLY ELECTRICITY BILLS?

RM...................

Appendix 2: Preliminary survey form (control group)

C. COMFORT LEVEL IN BEDROOM
(To be answered directly by the user(S) of a bedroom)

Respondent	A	B		A	B
Profession:			Age:		
Gender:			Health:		

14. DO YOU USE ELECTRIC FAN AT NIGHT IN THE ROOM?

1	Use it all night Long		3	Do not use it at all	
2	Use it half of the night				

15. HOW OFTEN DO YOU USE IT RECENTLY?

1	Everyday		3	Occasionally	
2	Almost everyday		4	Never	

16. WILL YOU BUY AN AIR CONDITIONING UNIT? PLEASE ELABORATE THIS DECISION

17. DO YOU USE A BLANKET TO GO TO SLEEP AT NIGHT?

		A	B			A	B
1	No Blanket at all			3	At certain time of the night		
2	Use it all night long			4			

18. WHAT TYPE OF BLANKET DO YOU USE?

		A	B			A	B
1	No Blanket			3	Thick sheet		
2	Thin Sheet			4	Comforter		

19. WHAT ARTICLE OF CLOTHING DO YOU WEAR TO SLEEP?

		A	B			A	B
1	No shirt			13	Night Gown (maxi)		
2	Singlet			14	Shorts		
3	T-shirt short sleeve			15	Bermuda		
4	T shirt Long Sleeve			16	Pajamas Bottom		
5	Sweater			17	Track Bottom (Thin)		
6	Pajamas (top)			18	Track Bottom (Thick)		
7	Kaftan			19	Kain Batik/Pelikat		
8	Night gown (mini)			20	Socks		
9	Night Gown (midi)				Others (Please Describe)		

20. HOW DO YOU RATE THE ROOM TEMPERATURE DURING THE NIGHT?:

	Hot	Warm	Slightly warm	OK	Slightly cool	Cool	Cold
	3	2	1	0	-1	-2	-3
A							
B							

21. PLEASE RATE THE AIR QUALITY DURING THE NIGHT:

	Very Dry	Dry	OK	Stuffy	Very stuffy
	2	1	0	-1	-2
A					
B					

Script: Thank you for your cooperation. In gratitude, we would like to present you with a small token for your help. On top of this survey, we will conduct a one-week monitoring of selected houses. In this monitoring we will leave the respondent with a datalogger for a week. It is a small device which will record the temperature and humidity at 5 minutes interval. We would also require a form to be filled on a daily basis. In this regard we would like to ask you:

22. ARE YOU WILLING TO TAKE PART IN OUR ONE WEEK STUDY?

1	Yes		2	No	

Appendix 3: Description checklist of monitored room

Appendix 3: Description checklist of monitored room

CHECKLIST FOR DETAIL MONITORING OF AN AIR CONDITIONED ROOM.

Housetype:	
Sample no:	Address:
Date Monitored:	

A DESCRIPTION OF THE AIR CONDITIONED ROOM

PLAN (INDICATE NORTH DIRECTION)

Room Dimension	
Location	
Room use	

Please indicate on the plan location of windows and AC units

Element	Int/Ext	Construction	Orientation	Glazing	Shading
Wall 1					
Wall 2					
Wall 3					
Wall 4					
Floor			X	X	X
Ceiling			X	X	X

B DESCRIPTION OF SYSTEM/UNIT

Location	
Type of system	
Model/ Brand Name	
Wattage	
Control Type	

Appendix 3: Description checklist of monitored room

C ENERGY EFFICIENCY MEASURES

a. Shading of external wall(s)

1	No shading	
2	Awning/lattice	
3	Balcony	
4	Trees	

5	Other Building	
6	Hill.	
7	Others (Please describe)	

b. Leakiness

1	Very leaky	
2	Normal	
3	Air tight	

D HOW MANY PEOPLE USE THIS ROOM? ....

E OTHER HEAT GENERATING APPLIANCES IN THE ROOM

1	TV	
2	Printer	
3	Telephone Fax	
4	Computer	

5	Fridge unit	
6	Spotlights	
7	Ceiling Fans	
8	Others (Please state)	

Appendix 4: Preliminary survey daily Log sheet (operation of AC)

Appendix 4: Preliminary survey daily Log sheet (operation of AC)

Appendix 4: Preliminary survey daily Log sheet (operation of AC)

Daily Log Sheet (To be filled by occupant)

Address:	Case no:
	Room:
	Location
	Monitoring start date :
	Monitoring end date :

Instruction

1. This form is to record the activity of a particular Air Conditioning unit selected
2. Please indicate the occupancy of the house for the day. Encircle H for at home, and A for Away.
3. For temperature, please state the actual temperature set.
4. For fan setting, please encircled L for Low, M for medium and H for High

Day 1 (Day.:........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Day 2 (Day.........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Day 3 (Day.........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Day 4 (Day.........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Day 5 (Day.........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Day 6 (Day.........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Day 7 (Day.........Date:.........)	H/A	H/A	H/A	H/A
Temperature				
'Fan Setting'	L M H	L M H	L M H	L M H

Appendix 5: Survey forms and checklist for field study

Case number:
Date of monitoring:
Enumerator:

Form no. 1
Thermal Comfort Field survey

Jabatan Senibina, Fakulti Rekabentuk dan Senibina,
Universiti Putra Malaysia
45300 Serdang

Note:
The information gathered in this survey are strictly confidential and will be used solely for the purpose of this study.

Details of household:

Address:...

House type:..

Number of occupants: ....

Guide to fill in the survey forms:

1. Respondent 1 form: To be filled by the first respondent
2. Respondent 2 form: To be filled by the second respondent
3. Air-conditioning unit operation form: to be filled by the respondent responsible for the operation of the units, including turning on, turning off, adjustment of temperature and/or blower fan setting, indicating the time of operation.
4. Auxiliary fan use and opening and closing window form: To be filled by the respondent respondible for the operation of auxiliary forced convection fan and the opening/closing of windows

Case no:

Form 2: Respondent number 1 ☐ 2 ☐

(To be filled by respondent at the time going to sleep, waking up in the middle of night (if any) and of waking up for the day)

Details of respondent:

Age:........................ Sex: ....

1. Thermal Sensation votes : Please state the time you go to sleep, waking up in the middle of the night (if any) and the time you wake up for the day and the corresponding thermal sensation you feel at the time. Indicate the sensation by marking √ in the corresponding space

Thermal sensation		Cold	Cool	Slightly cool	OK	Slightly warm	warm	hot
Going to bed	.........pm/am							
Mid sleep waking up (if any)	1)............am							
	2)...........am							
	3)...........am							
Waking up for the day	..............am							

2. Humidity sensation votes: Please indicate the humidity sensation you feel at these times. Indicate the sensation by marking √ in the corresponding space

Humidity sensation		Humid	Slightly humid	OK	Slightly dry	Very dry
Going to bed						
Mid sleep waking up (if any)	1					
	2					
	3					
Waking up for the day						

3. Use of blanket: Please indicate the type of your blankets you use (mark √).

Normal blanket: ☐ Comforter ☐

Please indicate the time of use and the extend of use

Time of use	Did not use	Half body	Full body
Early sleep			
Mid sleep			
Time of waking up			

(Please continue to the next page........)

4. Clothing articles

Please indicate the article of clothing you use for sleeping

Article of clothing	Use (mark √)
No shirt/top	
Undies	
Bra	
Singlet	
Short-sleeve t-shirt	
Long Sleeve t-shirt	
Sweater	
Pyjama top	
Pyjama bottom	
Kaftan	
Sleeping gown (mini)	
Sleeping gown (midi)	
Sleeping gown (maxi)	
Shorts	
Bermuda	
Track bottom (thin)	
Track bottom (thick)	
Sarong	
Socks	
Other (please indicate)	

Notes:

Form 3: operation of air conditioners

This form is to be filled in every time operation on the units is being carried out.

1. Time of switching on and off

Please state the time the units were being turned on and turned off. Please indicate the temperature setting and the blower fan setting opted.

Turning on				Turning off	
Time of turning on	Temperature	The person responsible or write T if timer is being used.	Blower fan setting (L=Low, M=medium, H=high, A = Auto) (Please encircle)	Time of turning off	The person responsible or write T if timer is being used.
			L M H A		
			L M H A		
			L M H A		
			L M H A		
			L M H A		
			L M H A		
			L M H A		
			L M H A		

2. Adjustment to the unit's operation

Please state the time adjustment being done to the operation of the units. Also please state the new temperature setting and new blower fan speed setting:

Time of adjustment of control	Original temperature setting	New temperature setting	Original blower fan speed (encircle) (L=Low, M=medium, H=high A=auto)	New blower fan speeed (encircle) (L=Low, M=medium, H=high A= auto)	The person responsible
			L M H A	L M H A	
			L M H A	L M H A	
			L M H A	L M H A	
			L M H A	L M H A	
			L M H A	L M H A	
			L M H A	L M H A	
			L M H A	L M H A	
			L M H A	L M H A	

Form 4: use of auxiliary fans

This form is to be filled by occupants every time the use and operation of auxiliary forced convection cooling fan being used

1. Please indicate the type of auxiliary fan used (Ceiling, standing, table etc) ....
2. Please state the time the fan is being switched on and off and the speed setting opted.

Time fan turned on	Time fan turned off	Fan speed (encircle)	Responsible person (respondent no)
		1 2 3 4 5	
		1 2 3 4 5	
		1 2 3 4 5	
		1 2 3 4 5	
		1 2 3 4 5	
		1 2 3 4 5	
		1 2 3 4 5	
		1 2 3 4 5	

3. Please state the time any adjustment being carried out to the operation of the fan (if any)

Time of adjustment	Original fan speed (encircle)	New fan speed (encircle)	Responsible person (respondent no)
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	
	1 2 3 4 5	1 2 3 4 5	

Notes:

Thank you for your participation

-END-

Appendix 6: Datasheet for Selected Households

Environmental condition summary

M2023

	Internal							external		
	Air temperature ta (°C)	Globe temperature tg (°C)	Relative Humidity RH (%)	Mean radiant temperature tr (°C)	Air velocity va (m/s)	Operative temperature to (°C)	Abs Humidity (gm/M3)	Air temperature T(*C)	Relative humidity RH (%)	Abs Humidity (gm/M3)
Overall										
Max	33.49	34.37	64.90	34.79	0.23	34.14	21.10	34.01	57.30	18.80
Mean	27.89	28.96	56.51	29.51	0.08	28.69	15.68	31.66	53.79	17.80
Min	23.78	25.73	45.20	25.81	0.01	25.33	9.40	30.31	39.40	14.50
Median	25.39	26.49	57.00	27.55	0.08	26.09	14.40	31.52	55.30	17.90
Mode	24.28	26.19	58.40	33.18	0.08	25.95	20.90	31.12	55.80	17.70
SD	3.86	3.33	4.58	3.11	0.03	3.46	3.70	0.76	3.54	0.79
While AC in operation										
Max	32.31	32.61	64.40	33.60	0.23	32.52	20.60	31.52	61.00	18.60
Mean	24.95	26.53	56.25	27.33	0.07	26.14	12.89	30.32	57.52	17.73
Min	23.78	25.88	45.20	26.12	0.01	25.38	9.40	29.10	54.30	17.00
Median	24.78	26.23	56.75	27.07	0.07	25.88	13.10	30.31	56.60	17.80
Mode	24.28	26.19	60.30	27.07	0.07	25.95	14.40	31.12	60.20	17.80
SD	1.06	1.08	5.19	1.24	0.03	1.04	1.75	0.65	2.04	0.26

Profile type	1
Adjustment type	2
Ceiling fan operation	3

AC Operational events				
Descr	Time	To i	Te	PMV actor
Turn on	11:00 PM	32.6	31.5	2.53
turn off	7:00 AM	25.6	25.6	0
adj 1				
adj 2				
adj 3				

PMV while AC is on (Produced by INFOGAP)	RESP 1				RESP 2			
	PMV ()	PPD (%)	PMVadj	PPDadj	PMV ()	PPD (%)	PMVadj	PPDadj
Max	1.84	100.00	2.45	92.27	1.89	99.94	2.55	92.17
Mean	-2.72	93.88	0.26	8.58	-2.43	90.25	0.36	8.48
Min	-3.81	5.03	-0.19	5.00	-3.46	5.65	-0.09	4.90
Median	-2.86	98.31	0.20	5.86	-2.57	94.78	0.30	5.76
Mode	-2.96	99.87	0.15	5.20	-2.54	94.15	0.25	5.10
SD	0.75	16.23	0.36	12.39	0.71	16.56	0.36	12.39

Cooling	Time	To	Stabilisation	time	to
start	11:00 PM	32.6	average		25.8
end	12:30 AM	25.6	start	12:30 AM	25.6
temp diff		-7.0	end	7:00 AM	25.6
duration		90.0	temp diff		0.0
gradient (celcius/min)		-0.08	Stabil duration		390.0
			gradient (celcius/min)		0.00

notes:

M2023

Adaptive Behaviorial Summary

M2023

Respondent 1		
Age	Sex	Health
36	male	ok
TSV		
Sleep time	11:00 PM	0
1	1:00 AM	0
2		
3		
got up	7:00 AM	0
Humidity		
Sleep time		0
1		0
2		
3		
got up		0
Covers		
Thickness		1
use 1		1
use 2		1
use 3		1
Clo		
T shirt lengan pendek		0.09
Sarong		0.18
	Total	0.27

Respondent 2		
Age	Sex	Health
32	female	ok
TSV		
Sleep time	11:00 PM	0
1	2:00 AM	0
2		
3		
got up	6:30 AM	0
Humidity		
Sleep time		0
1		0
2		
3		
got up		0
Covers		
Thickness		1
use 1		1
use 2		2
use 3		2
Clo		
T shirt lengan pendek		0.09
S trek nipis		0.2
P		0.03
B		0.01
	Total	0.33

AC unit operations						
AC on off	Time	(value)	Actor	Temp	Fan	
ON	11:00 PM	5	1	26	A	
OFF	7:00 AM	13	1			
			h	m	total(m)	
Total operating hour			8	0	480	
AC adjustment						0
Time	(value)	T1	T2	F1	F2	Actor

Fan on off						
	Time	(value)	Actor	Speed		
On	7:00 PM	1.00	1	3	h	4
Off	11:00 PM	5.00	1		M	0
						240

Fan adjustment				
Time	Value	s1	s2	Actor

Equivalent Clothing index at minimum vote time

	Time	PMV	clo	Vote	I_{EQUIV}	PMV adj	I_{ADJ}
R1	1:00 AM	-3.00	0.27	0	1.6	3.00	1.33
R2	2:00 AM	-2.48	0.33	0	1.6	2.48	1.27

case	M2023
Adress	Jln Perdana 2/4, Puchong Perd
House typ	2 storey Link Int
Owner	Azizothman
Start date	09/02/2005 18:02
End date	10/02/2005 7:57

Neutral temp (PMV=0)		
	R1	R2
Temp (To)	25.6	25.7
Time	12:27 AM	1:15 AM
Value	6.42	7.25

M2023

Environmental condition summary

M2025

	Internal							external		
	Air temperature ta (°C)	Globe temperature tg (°C)	Relative Humidity RH (%)	Mean radiant temperature tr (°C)	Air velocity va (m/s)	Operative temperature to (°C)	Abs Humidity (gm/M3)	Air temperature T(*C)	Relative humidity RH (%)	Abs Humidity (gm/M3)
Overall										
Max	29.93	30.01	83.10	32.20	0.51	29.98	34.90	30.71	86.60	23.80
Mean	21.97	22.44	63.85	23.08	0.25	22.41	14.22	27.96	76.06	20.71
Min	16.61	17.30	56.70	16.13	0.00	17.28	8.10	24.01	35.70	8.50
Median	19.70	20.42	59.60	21.45	0.33	20.36	13.90	27.91	80.60	21.90
Mode	29.09	17.49	59.00	29.02	0.00	17.47	8.30	26.73	84.00	21.30
SD	4.77	4.56	6.38	4.25	0.18	4.55	5.96	1.50	11.67	3.49
While AC in operation										
Max	21.64	22.67	62.60	23.98	0.51	22.58	11.00	29.50	85.30	23.80
Mean	18.23	18.95	58.95	19.95	0.38	18.92	8.81	27.86	82.26	22.19
Min	16.61	17.34	57.80	18.12	0.24	17.28	8.10	26.73	78.80	21.30
Median	17.98	18.63	58.80	19.62	0.38	18.62	8.60	27.91	82.80	22.10
Mode	16.84	17.49	59.00	18.72	0.37	17.47	8.30	27.91	84.00	21.80
SD	1.22	1.29	0.76	1.39	0.05	1.29	0.65	0.81	1.85	0.66

Profile type	2
Adjustment type	2
Ceiling fan operation	3

AC Operational events				
Descr	Time	To i	Te	PMV actor
Turn on	10:07 AM	29.26		
turn off	6:00 AM	17.31		
adj 1				
adj 2				
adj 3				

PMV while AC is on	RESP 1				RESP 2			
	PMV ()	PPD (%)	PMVadj	PPDadj	PMV ()	PPD (%)	PMVadj	PPDadj
Max								
Mean								
Min								
Median								
Mode								
SD								

Cooling	Time	To	Stabilisation	time	to	PMV
start	10:15 PM	29.01	average			
end	6:00 AM	19.15	start			
temp diff		-9.86	end			
duration		473.00	temp diff		0.00	
gradient (celcius/min)		-0.02	Stabil duration			
			gradient (celcius/min)	#DIV/0!		

notes:

M2025

Adaptive Behaviorial Summary

M2025

Respondent 1		
Age	Sex	Health
25	F	ok
TSV		
Sleep time	10:30 PM	1
1	4:00 AM	-2
2		
3		
got up	6:00 AM	-2
Humidity		
Sleep time		0
1		1
2		
3		
got up		1
Covers		
Thickness		1
use 1		1
use 2		2
use 3		2
Clo		
Singlet		0.08
Shorts		0.06
P		0.03
Total		0.17

Respondent 2		
Age	Sex	Health
TSV		
Sleep time		
1		
2		
3		
got up		
Humidity		
Sleep time		
1		
2		
3		
got up		
Covers		
Thickness		
use 1		
use 2		
use 3		
Clo		
Total		0

AC unit operations					
AC on off	Time	(value)	Actor	Temp	Fan
ON	10:07 AM		1	16	A
OFF	6:00 AM		1		
			h	m	total(m)
Total operating hour			7	53	473

AC adjustment						0
Time	(value)	T1	T2	F1	F2	Actor

Fan on off	Time	(value)	Actor	Speed		
On	7:00 PM		1	3	h	0
Off	7:20 PM		1		M	57
On	9:40 PM		1			57
off	10:15 PM		1			
on	6:20 AM		1			
off	6:30 AM		1			

Fan adjustment				
Time	Value	s1	s2	Actor

Equivalent Clothing index at minimum vote time

	Time	PMV	clo	Vote	I_{EQUIV}	PMV adj	I_{ADJ}
R1			0.17			0.00	-0.17
R2			0			0.00	0

case	M2025
Adress	
House type	
Owner	
Start date	2/13/05 7:00 PM
End date	

Neutral temp (PMV=0)	R1	R2
Temp (To)		
Time		
Value		

M2025